Final Report

Period of Performance:
1 October 2003–30 September 2005

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13. ABSTRACT *(Maximum 200 words)*

Substantial benefits in ship design and operating economies are expected to accrue to the Navy if electric ship propulsion techniques can be successfully developed and introduced in the future Navy fleet. One area of interest toward this end is in superconducting homopolar motors. This report surveys prior data, reports, papers, and other studies that relate to superconducting homopolar motors. It also includes summaries of discussions held by the author with General Atomics, the Naval Surface Warfare Center, and the Office of Naval Research on the subject.

14. SUBJECT TERMS
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FINAL REPORT

Period reported: 1 October 2003 through 30 September 2005

1. Contract Summary

- Grant number: N00014-04-1-0064
- Period of performance: 1 October 2003 to 30 September 2005
- Total value of awarded Grant: $39,243.00

2. Contract Personnel

The Key Person involved in this effort was Dr. Ian R. McNab, Principal Investigator. Dr. McNab is a Senior Research Scientist at The University of Texas at Austin and Director of the Electromagnetic Systems Division (ESD) at the Institute for Advanced Technology (IAT). He has had extensive prior experience and involvement in superconducting homopolar generators and motors and in the development of fiber and other brushes for these and similar machines. Toward the latter part of 2004, Dr. Chadee Persad of the IAT became involved in work to evaluate the debris produced by worn metal fiber brushes. Dr. Persad is also a Senior Research Scientist at UT and is the Team Leader on High-Performance Materials at the IAT.

3. Introduction and Future Naval Relevance

Substantial benefits in ship design and operating economies are expected to accrue to the Navy if electric ship propulsion techniques can be successfully developed and introduced in the future Navy fleet. Several different concepts have been evaluated over the last few decades. One important technology that offers significant operating benefits is the use of high temperature superconducting materials. Such materials allow the operating magnetic fields in motors and generators to be increased significantly compared with conventional (ferromagnetic or iron-cored technology) machines, thereby providing attractive operating system power densities. At the present stage of superconductor development, it is easier to envision the use of superconducting technology in direct current (DC) machines than in alternating current (AC) machines. One important class of such DC machines is known as homopolar (sometimes also referred to as "unipolar" or "acyclic") machines. A very important feature of such machines is that all the machine power has to be transferred through a sliding interface comprised of brushes that operate on sliprings. Several features are important in achieving an optimum current transfer system of this type, including:

- the sliding contact must operate stably mechanically, electrically and thermally;
- the electrical and frictional losses must be acceptably small;
- the wear rate of both the brush and slipring must permit acceptable operating life;
- access to the sliprings must be made available for inspection and replacement (if required).

A complicating feature of this type of machine is that the slipring on which the brush slides may intersect the magnetic field in such a way that internal circulating currents are created that

may adversely affect the brush operation and performance. The adverse effects of this can be alleviated by suitable design of the slipring.

Developments in this area are presently being pursued by General Atomics (GA), a Contractor for the Office of Naval Research (ONR), in a program that has led to the design, fabrication and test of a multistage prototypic 3.7 MW superconducting motor that uses metal fiber brushes.

4. Statement of Work

As noted in Section 2 above, the Principal Investigator for this study has had considerable prior experience in the development of current transfer systems of this type. Hence, the objective of this study was to transfer this experience to the present ONR and GA project team. The Statement of Work for this Grant called for:

The Principal Investigator will retrieve prior data, reports, papers and other studies that relate to homopolar machine developments and brushes that may be suitable for use in such machines. In addition, he will visit GA (San Diego) for three meetings with the ONR/GA project team for discussions on these topics and the machine testing program. Also, he will visit the Naval Surface Warfare Center in Philadelphia to review testing of the superconducting homopolar test machine. These discussions will be summarized in written reports and a final report will be provided at the conclusion of this effort.

5. Technical Report

5.1. Background

The support being provided by the IAT for ONR on this program is focused on the issues relating to the brushes being used and developed to transfer the load current to the superconducting homopolar motors being developed by General Atomics (GA) for ship propulsion. In common with earlier experience in the brush field, significant polarity differences have been observed during brush system tests at GA. The fundamental reasons for these polarity differences are not well understood, despite prior attempts to explain the effects. Generally it is found that the brush having a positive polarity operates with significantly higher voltage drop and wear rate than the brush having a negative polarity. From the GA data, it seems that the negative brushes will have a lifetime that is acceptable for fleet operation, but the wear rate of the positive brushes is questionable and may demand more frequent replacement than can be tolerated in fleet operation.

5.2. Integrated Project Team Meetings

Under the auspices of this grant, the IAT has been invited to participate in meetings of the integrated product team (IPT) set up by the Office of Naval Research (ONR) with GA. These meetings were generally scheduled on a quarterly basis. During this contract period, Dr. McNab, attended the following meetings and provided comments to ONR:

Table I. Meeting Attendance

Date	Place	Meeting type	IAT person	Report provided
8 Dec 2003	Anteon, Washington	Qtrly. Progress Review	Dr. McNab	See Appendix A[1] of this report
19 Feb 2004	Anteon, Washington	Workshop on Brushes and Brush Holders	Dr. McNab	See Appendix B and Appendix G
13-14 Apr 2004	GA, San Diego	Qtrly. Progress Review	Dr. McNab	See Appendix C
20-22 Oct 2004	Anteon, Ballston	IPT Meeting #2	Dr. Persad	
30 Nov 2004	Anteon, Ballston	IPT Meeting #3	Dr. Persad	Briefing given on: "Contact Materials Performance" – see Appendix D
16-17 Dec 2004	GA, San Diego	Homopolar Brush Workshop	Dr. Persad	

5.3. GA data

Dr. McNab has received and reviewed test data and reports provided by GA and Anteon during the duration of this effort. Where appropriate, comments have been provided verbally, by email or in written documents to GA and ONR personnel. In this regard, Dr. McNab signed a GA Non-Disclosure Agreement agreeing to protect the confidentially of the data thus provided.

5.4. Basic Studies on the Oxidation of Copper

During the summer of 2004, Dr. Persad supervised a student, Mr. Eric Bierschenk, who investigated some basic aspects of the oxidation of copper. These studies, which are described in IAT Paper P.0742, were focused on the effects of a marine environment on electric railgun components such as copper rails and were not funded under this grant. However, they may also be applicable to the copper-fiber brush environment within the GA machines and are therefore included here as Appendix E.

5.5. Early Work on Fiber Brushes

The early work carried out on fiber brushes is summarized here in Appendix F, which should be read in conjunction with the briefing given at the 19 February 2004 meeting (see Appendix G).

6. Expenditures:

Monthly financial statements have been provided, and a final invoice will also be provided, as required by the contract.

[1] With the benefit of hindsight, some of the comments in these Appendices have been amended and updated to improve their relevance.

APPENDIX A

Memo to: Ellie Martin (ONR) and Will Creedon (GA)
Subject: Comments on the Superconducting Homopolar Motor Quarterly Review No. 8 held at Anteon on 8 December 2003
From: Ian R. McNab (UT-IAT)
Date: 12 December 2003

1. INTRODUCTION

Thank you for inviting me to attend the meeting. It was both very interesting and also reminiscent of previous projects that I have been associated with, both in the U.K. and U.S. These included early efforts at the IRD Co. Ltd., in Newcastle, England from about 1964 to about 1972, Westinghouse R& D Center in Pittsburgh, PA from about 1975 to 1982, and passing involvement with the NSWC Annapolis superconducting ship propulsion program from the 1970's and 80's. While at IRD and Westinghouse I was considerably involved in the current collection portion of the programs. This involved the development of brushes that utilized solid metal-graphite blocks, metal-plated carbon fibers, metal fibers or liquid metal systems.

The discussions were both interesting and well done. There is clearly a concern about the performance of the HiPerCon brushes, and I have provided more comments below.

2. GENERAL COMMENTS

The essential feature of homopolar machines, in contrast to most other electrical machines that are commonly encountered, is that **ALL** of the machine power has to be transferred through the brush or current collection system. This necessarily involves current transfer across a sliding interface. The difficulty of doing this successfully for long periods of time, together with the relatively low voltage and therefore high current requirements of these machines, is why early efforts (in the late 19th Century) to use homopolar generators for electric utility systems were displaced by the introduction of the AC machines that we know today, which were developed primarily by Tesla and Westinghouse - in strong competition with Thomas Edison.

Nevertheless, the homopolar machine has some features that make it of interest for specialized applications. One of these is that there is no armature reaction of the applied current on the field windings (since the forces are orthogonal), which is attractive for a super-conducting coil system where substantial disturbances to the field winding can cause it to go "normal". Together with the prospect of low electrical and acoustic noise, these are the most likely reasons why ONR is considering it today for ship propulsion under the GA Contract.[2] Nevertheless, one should not forget this essential brush requirement. In short, designing the machine without being *fully cognizant* of this aspect is likely to lead to unrealistic expectations that can be hard to achieve. Often in the past I have seen organizations that have been interested in homopolar machines fail to appreciate this fact, with the result that disappointments occur as the program progresses.

I make these comments because I get some sense that this may have already happened on this program and I want to (a) guard against unrealistic expectations for the program and (b) help

[2] I have not had access to the GA proposal and do not know what advantages or features were claimed in that proposal. However, the aspects mentioned above have been the most common ones used in the past to support the development of super-conducting machines for this application.

you to understand the difficulties that the brush designers face, so that they can be better supported. It is not a feasible approach to "design" a machine on the basis only of the super-conducting magnets and the size and weight constraints demanded by the user, without fully appreciating the brush system requirements and its operation. Since the brushes are at the heart of the machine operation (and generally, literally, at the heart of the machine structure), the brush designers must be given an equal seat at the table when all system aspects of the machine are being discussed, and their difficulties have to be appreciated by all concerned.

From the comments I have heard, it appears that the program started without an evaluation of brush system options. That is, the HiPerCon brushes were selected as the preferred brush supplier from the beginning of the program. Although the little information I have seen about these brushes is promising, this may or may not have been the correct solution - it is too early to tell (at least for me). The fact that the wear of the positive brushes is higher than expected (and desired) and that no solution appears to have yet been achieved by HiPerCon is clearly a concern. I have seen no information that indicates that HiPerCon understands this issue, nor have I seen a proposed solution from HiPerCon. (That is not so say that HiPerCon may not have such understanding or solutions but merely to say that they have not been revealed or discussed in my presence.)

3. HISTORICAL PERSPECTIVE ON CURRENT COLLECTION

I don't want to dwell on the past too much but a few comments on the general development of brushes may be useful in case you are not familiar with the subject – and in view of the importance for this type of machine. If you are familiar with all of this I apologize.

As a general rule, one has to balance multiple factors in evaluating the performance of the brush or current collection system. For a solid brush these include:

(i) The electric voltage drop across the interface.

This voltage drop multiplied by the current density transferred by the brush defines the electrical portion of the dissipation at the brush site (Watts/m^2).

(ii) The friction coefficient at the sliding interface

This friction coefficient multiplied by the sliding speed and the brush pressure normal to the interface defines the mechanical losses (Watts/m^2).

(iii) The brush life

(iv) The slipring life

(v) Necessary auxiliaries

These might include temperature control, atmosphere control, debris wear management, etc.

The general perversity of life seems to ensure that one cannot easily achieve all of the goals that one would like to have for all of these parameters. Of course, in many cases what we can achieve is acceptable – but we always want more! Solid brushes (as used in many everyday devices) are generally optimized to have a brush operating pressure that provides approximately equal electrical and mechanical losses, although the tendency is to operate on the higher pressure side of this optimum because the consequences of too low a brush pressure is lack of a good contact and, should this deteriorate into an arcing situation, this is generally more damaging to the slipring surface than operating with a somewhat higher pressure and accepting higher frictional losses.

3.1. Liquid Metals

The disk homopolar was the first electrical machine studied by Michael Faraday in the 1830s. He used liquid mercury as the way to make contact with the periphery and the axis of the disk. Liquid metals of various kinds have been investigated for this purpose until recently, although there are only a limited number of acceptable candidates that are liquid at or near room temperature. Broadly speaking, liquid metals have the following characteristics.

a) Liquid mercury has a high density and therefore has high viscous losses which make it generally unacceptable for homopolar generators that have relatively high peripheral speeds. Operating conditions for low speed motors (such as GA and ONR are developing) are easier but the overwhelming opinion these days is that the toxicity of mercury makes it an unacceptable choice.

b) An attractive choice from the electrical conduction and low density aspect is the alkali metal sodium and, more commonly, one of the eutectic alloys with potassium, (NaK) that has a melting temperature below room temperature. Several machines have been built with this material, including most recently, the NSWC Annapolis super-conducting machines. The difficulties with this material are its well-known reactivity with water (and even humid air) and its tendency to form highly reactive super-oxides that have caused severe personnel injury on more than one occasion. It is therefore necessary to maintain tight control of the machine environment through careful atmospheric control and monitoring and it is also necessary to continuously circulate the NaK through some form of filtration and purification system to maintain cleanliness of the liquid.

   Given the objective of the ONR/GA program, my personal feeling is that the use of liquid metals is not advisable, despite the Navy's investment in this area in the 1970's and 80's. I believe that the Captain and crew of a ship would not be comfortable knowing that ingress of water into the main propulsion machinery could lead to an explosion as well as loss of propulsion.

c) The third class of metals that have been investigated are the low melting point alloys composed of indium, tin, gallium and other materials. These are intermediate in density between NaK and mercury, so that viscous losses are correspondingly intermediate. However, they also have a considerable tendency to oxidize and when this happens the liquid can quickly become very viscous and may even solidify. The experience base with these materials has been less than with the other two classes of liquid metal and I am not aware of a strong following for these materials at present, although I know that Dr. Neil Sondergaard conducted much research in this area.

I have conducted experiments with all of these materials and, frankly, would not recommend any of them to you for this program.

3.2. Brushes and Electric Machines – the Early Days[3]

Towards the end of the 19th Century when electrical machines of various kinds, including homopolars, were being developed, a variety of brush configurations were used. The first and

[3] There have been a number of notable developments in the area of brushes and the comments made here obviously represent only one person's view of these topics.

most prevalent type for a while was the brush composed of metal wires or fibers which looked like a paint brush. Indeed, this is why the brushes we use today are called "brushes" - even though they are generally a "carbon/graphite"-based material. These wire brushes were used for homopolar machines and also for the primitive commutating machines that were then being developed, together with brushes composed of bundles of metal foils. However, the nature of commutation (which is when the brush leaves a slipring segment and moves onto another one that is connected to a different circuit in the machine) proved to be extremely harsh for the metal fiber and foil brushes. An amusing description of this is provided by Edison is describing the severe deterioration of metal brushes on commutated motors that were being used for electric trains. What then happened was that a colleague of Edison's (named VanDerpoele) realized that the brush was being asked to commutate (or "turn off") the current in one slipring segment and turn on the current in the next segment. Because the metal wire brush did not have any significant resistance in the peripheral direction, it was subjected to an internal circulating current that quickly destroyed it. VanDerpoele suggested the use of a material with high circumferential resistance (graphite) and, even though this had higher resistance to the load current and hence higher electrical losses, it solved the commutation problem and spawned the "carbon" brush industry we know today. (Thus, metal fiber brushes were entirely replaced and largely forgotten for many years until the ONR current collection program was put in place at the Westinghouse R&D Center in Pittsburgh, PA in the late 1970's.)

This change in machine and brush technology proved very successful and homopolar machines were also largely relegated to niche applications in the early 20th Century. Such applications included ones where the generation of very high currents was needed, as in certain chemical processes. Since carbon brushes were widely used in other machines, these were also accepted for the homopolar machines (most of which were generators) although in some cases modifications were made to introduce a metal component into the brush to enhance current transfer. (Pure carbon or graphite brushes may have voltage drops of 2 to 4 volts and, although this may be acceptable for high voltage sliprings, it represents too high a loss for homopolar machines.) Thus, a range of metal-graphite brushes was created and is produced by the brush industry today. Most of these have some fraction of copper mixed with the graphite-carbon matrix, although silver-graphite brushes are also used in specialized situations, generally for instrumentation rather than high current transfer. Such brushes have a wide range of friction coefficients and voltage drops and the existing commercial brush industry is able to advise on what is best for each application, provided that the conditions fall within their area of expertise. Because graphite needs to have a certain amount of water vapor present to ensure easy sliding of the lamellar graphitic sheets, there are a few situations where other materials are used. For example, molybdenum disulphide may be added to brushes used in high altitude aircraft to ensure good operation in low humidity conditions and more rarely, niobium diselenide (another dichalcogenide with lamellar structure) was used in the camera used by the Apollo 11 astronauts in the near-vacuum conditions on the Moon.

3.3. IRD Co. Ltd and Fiber Brushes

The IRD Co. Ltd. in Newcastle, England made the first ever superconducting homopolar generator in 1964 under the direction of Tony Appleton. This was a 50 hp machine and it was donated to the Science Museum in London (and may still be there). Following this in 1967, an ambitious program was created to build a 3250 hp machine that became known as the Fawley motor. This was intended for use as the drive motor for a low speed (about 200 rpm) cooling

pump at the Fawley power station near Southampton, U.K. The machine had an NbTi magnet and a warm bore of about 2 meters diameter. The machine used a double disk rotor that was segmented and connected in a special way to avoid brush shorting problems. The brushes used were commercially available and made by the Morganite company of Swansea, Wales, UK. The grade used was CM1S and this was chosen on the basis that it had been tested and used in the very large (550 MJ) iron-cored homopolar generator at the Australian National University (ANU) in Canberra. The engineer who did this testing and worked with the Morganite engineers was Richard Marshall[4]. Despite this background, problems were encountered with the CM1S brushes and an effort was started to evaluate alternatives. I was involved with that and Richard Marshall also spent some months at IRD on Sabbatical leave from the ANU to help in this effort. One of Marshall's approaches was to look at brushes composed of a few thick copper-graphite wires. These wires, about $1/16^{th}$ of an inch in diameter were composed of drawn down copper tubes that were filled with graphite powder. The objective was to achieve the right balance of good electrical contact voltage drop and low friction that is essential to any good brush system. These were tested by Marshall but I cannot recall the results. It was clear, however, that they lacked significant flexibility.

At about the same time, carbon fibers were being developed by the Royal Aircraft Establishment in Farnborough, England. These were carbonized PAN (PolyAcrylicNitrile) materials. Following the development work at IAT on the super-conducting machines, the Royal Navy took an interest in the technology for possible use in submarines. Recognizing the problems with brushes and apparently knowing about the early use of "brushes" the then Chief Scientist for the RN, Sam Bolshaw, suggested that IRD consider the use of carbon fiber brushes in place of the CM1S metal-graphite solid units. The idea from the start was that the large number of independently flexible contacts should ensure a low contact drop as the current would be spread more uniformly through the brush surface rather than just through a few "alpha spots" as in a solid (= rigid) brush. IRD thought that Mr. Bolshaw's idea was a good one and quickly made and tested some brushes. Typically these had 10^6 carbon fibers in a contact area of about one square inch. To our surprise, on testing these brushes, they were found to demonstrate *improved* performance as the tests progressed. After some investigation, this was found to be caused by wear particles from the slipring being caught up in between the fibers, thereby increasing the electrical conduction through the brush structure. The next step was therefore to consider how to make this change deliberately, rather than by chance. This was accomplished by a development by the chemists at the IRD who found a way to electroplate a tow (10,000 fibers) of carbon fiber on a continuous basis in a wet bath process. After being plated with copper, nickel, silver or a combination of such metals, the wet tow of plated material was wound, dried, stacked and cut to length and then soldered to a back plate to make a brush unit. Typical sizes were a brush area of about one square inch, but other sizes were also made, and a typical wear length was about one half of an inch. Many tests of these brushes were made over a wide range of conditions in the time period from about 1969 to about 1974 for application to homopolar motors and generators. Tests were done with different plating materials, with different slipring materials, in different atmospheres (including hydrogenic reducing atmospheres) and the tests results are still available to a limited extent. One aspect that was noted was that polarity differences were observed with negative brushes operating better than positive brushes. One idea that was developed, tested and patented (as many of these concepts were) was the idea of making an all negative brush system in which a rotating negative brush replaced the "normal" static

[4] Dr. Marshall worked at the IAT for a number of years and, having retired, lives in Austin, TX.

positive brush. A comment about this concept is to note that tests showed that the inherent flexibility of fibers was much reduced once the slipring was spun, especially at high speed for generator applications. As such, slipring wear was much increased.

One issue that was recognized throughout the development of superconducting machines at IRD was the need to match the slipring angle to that of the local magnetic field vector. The influence of this on brush operation was shown experimentally in measurements that I did with my colleagues, Geoff Wilkin and John Clarke, in 1974. In these experiments a solid copper-carbon brush was subdivided and insulated into five separate sections. This brush was placed on a stepped slipring and operated within the poles on an iron electromagnet. The current through each separate brush subsection was monitored. The results showed that the distortion of the current caused by the presence of a transverse voltage on the slipring clearly related to the induced transverse voltage as the magnetic field strength was increased. The criterion that I developed to measure this was the M number where M was defined as the ratio of the transverse voltage on the slipring to the sum of the positive and negative brush voltage drops (which may be approximated as twice a single average brush drop). For $M >> 1$, circulating currents will predominate and will be large. For $M << 1$, circulating currents will not add appreciably to the local current density in the brush. For $M \sim 1$, the local current density at one edge of the brush will be approximately double the usual value while that at the other edge will be near to zero. Clearly, for acceptable performance of the total homopolar generator system, the slipring should be machined to have an angle such that M is small. If this is not done, the brush life will suffer – as appears to be the case at present with the HiPerCon brushes. The extent to which the slipring should be matched to the magnetic field vector can be determined by evaluating M. As mentioned above, to prevent the local current density doubling under one edge of the brush, M must be $< \sim 1$. In situations where the magnetic field of the machine needs to be changed to modify its operating conditions (e.g., power), a judgment will need to be exercised as to what the optimum slipring match to the magnetic field vector needs to be to minimize overall brush wear and degradation.

3.4. Westinghouse R&D Center and the ONR Current Collection Program

I left England on March 18, 1975 and, with my family, flew to Pittsburgh to work for Westinghouse R&D Center. I started work there on March 18 and had my first business trip on March 20 to NSWC Annapolis for a meeting on electrical machines for ship propulsion. At that time, Westinghouse had built more than one NbTi superconducting machine in support of efforts to develop AC machine technology for baseload electric utility use. As a consequence, although they were aware of IRD's efforts in this area, they chose to develop an iron-cored homopolar approach for ship propulsion. This approach used several stages arranged in series electrically and was termed SEGMAG. Because of the use of iron, the stage voltage was low and the use of conventional brushes was discounted. Westinghouse therefore chose to develop a NaK-filled slipring and more than one machine was built and operated using this approach. However, as intimated in Section 3.2 above, the general problems associated with NaK eventually led to a decision to abandon that approach.

Attention then turned to the prospects for carbon fiber brushes and Westinghouse chemists[5] were able to successfully produce material that was similar to that made earlier by IRD in the U.K. Samples of fiber with copper, silver, nickel and gold platings were produced and

[5] Led by Dr. Herb Ricks.

tested.[6] Some of these tests were on segmented sliprings which, although not commutating, had similar requirements. The fiber brush, even with some modifications to increase the azimuthal internal resistance, was finally not judged satisfactory for this application. Nevertheless, developments continued with fiber brushes. Sample brushes were made and tested and were supplied to Dr. B. Robson at NRL for his use on a very high speed (470 m/s) homopolar generator that he was developing. This machine had encountered problems using solid metal-graphite brushes because the beryllium-copper material of which the rotors were made had an inherent granularity that did not provide a smooth running surface for the brushes, so that poor performance was obtained. Dr. Robson then turned to the more flexible metallized carbon fiber brush with some success.[7]

During these brush development efforts, funded by ONR, we (collectively) began to question the inherent assumptions and value of the fiber brush approach. One aspect of this was the inherent flexibility of the fiber, which we had evaluated in England on an individual basis, and the current carrying capability of a single fiber – which we tested experimentally at Westinghouse (and found to be very high). However, when bundled together into a brush, the claimed advantage of a million or so "independent" flexible contacts clearly was not being realized, so other approaches were sought.

Concurrently with the ship propulsion interests, the same team at Westinghouse was investigating a very high technology superconducting machine for a conceptual thermonuclear fusion program funded jointly by EPRI and DOE. Team members included LANL and CEM (initially). This machine was a large diameter (~ 2 meter) rotor immersed in the magnetic field of a large superconducting coil. The peripheral speed of this Homopolar Energy Transfer System (HETS) machine was high (~ 300 m/s) and the sliprings were arranged under the magnet coils so that the maximum flux could be cut and made to generate electrical power. The object of this series of machines was to power the pinch coils for the toroidal fusion reactor and then to accept power back from the plasma expansion after the short time fusion reaction had occurred. The machine operation was extremely severe, necessitating multi-gigawatt operation for short times alternately as a motor and a generator with an operating time of a fraction of a second and a cycle time of 10 seconds. As might be expected, the brush duty was correspondingly severe and the approach that was eventually developed was the "HETS brush module" that contained multiple wafers of solid brush material. These wafers were arranged with their thin dimension in the azimuthal direction. This was to minimize temperature build up under the brush. In this case, then, the "traditional" approach of current transfer through a single monolithic block was replaced by a few independently "flexible" (i.e., loadable) brushes. Incidentally, electrical contact to the brushes was made through commercially-available hard silver plated copper strips that were mounted in the brush box on each side of each brush wafer.

3.5. Metal fiber brushes

The next step in our progression of brushes was to look at metal fiber brushes. These were chosen on the basis that they had a number of independently-loaded fibers that were

[6] It was during this period (maybe about 1976) when we first made the acquaintance of Prof. Doris Wilsdorf. She had been supported by US Army ARO contracts for more than ten years and those contracts had come to an end. She was then brought to Westinghouse by Mr. Jack Satkowski of ONR – a project manager I had known from the U.K. and who was also project manager for the Westinghouse efforts. In the office of my boss at that time, Mr. John Mole, a sample of our finest gold-plated carbon fiber was produced and shown to Mrs. Wilsdorf. She took a piece of the fiber and this was the start of her interest in this area.

[7] Dr. Robson had tried to procure brushes from us at IRD in the U.K. but the company was not willing to provide them for commercial reasons.

intermediate between the carbon fiber assemblies (with perhaps a million potential contact points) and the HETS concept with perhaps ten independent brushes per unit. Dr. Phil Reichner and I then came up with the concept of the metal wire (or fiber) brush and he actively pursued that development, leading to at least one patent.

For further information - See Appendix F.

APPENDIX B

Comments to: Ellie Martin (ONR)
Cc: Will Creedon (GAT); Howard Stevens (Anteon)
Subject: Thoughts after the Brush Workshop on 19 February 2004
From: Ian R. McNab (UT-IAT)
Date: 2 March 2004

After some reflection following the Workshop, my views on what to do fall into four general categories, as described below.

- Push forward with the sub-scale machine building and testing program
- Develop brush alternatives to support the existing program
- Initiate some more fundamental R&D that could pave the way for better solutions for the full-scale machine
- Other comments

The best thing would be if all of the first three topics could be supported in parallel at some level. Clearly this depends on the funding available. The natural tendency is for the first task to sweep up all of the available funds. Hopefully this can be avoided.

A few more comments on each of these items are given below.

1. Push forward with the sub-scale machine building and testing program

The advantage of the tests on the subscale machine is that more data can be accumulated on brush performance – voltage drops, frictional losses and wear. The more data we can get, the better, especially if this leads to confidence about the brush lifetime.

The work being done by ZiBi seems the best that can be done at present with the existing brushes – i.e., put an "over-wrap" around the brush and hope that this helps to prevent the distortion experienced by the fibers. While this may work to some extent, I personally am not very optimistic about this as a long term solution. Also, the use of zinc is unusual as a brush material and I would expect corrosion to become an issue – but I am not a chemist so someone better qualified should address this issue.

2. Develop brush alternatives to support the existing program

I think that there are several alternatives that can be considered at the moment.

i) Buy and test some of the brushes developed by IAP Inc. The measured wear rates according to Dave Bauer were very low (~ 10^{-12}). Some of these brushes should be procured and tested in the GA test rig.
ii) Build and test the rotating positive (= negative contact) brush arrangement. Indications from the tests we did in the UK were that this worked there with metal-

plated fiber brushes. I would expect conditions to be considerably more favorable with the metal fiber brushes at the lower slipring speeds pertaining in the GA motors.

iii) Some of the lower cost brushes being developed by Shahin should also be tested at GA.

iv) Even though I am not sure that I agree with Dr. Lynch's comments concerning polarity differences, it does seem that it would be worthwhile to try out some of his solutions on the GA test rig.

v) Finally, even though ZiBi said that he had done tests with poor results, Westinghouse experience with conventional silver-graphite grades was quite good. Indeed Dave Bauer mentioned that in his talk (although then saying that the IAP Brushes were better) and referenced a wear rate of 1.7×10^{-11}, as I recall. If this could be achieved, it would be satisfactory for the required machine lifetime.

3. Initiate some more fundamental R&D that could pave the way for better solutions for the full-scale machine

A number of possible avenues spring to mind as to what could be done for the longer term. Since the program funding derives from CPUs, there may not be much of a lobby for this at the moment. On the other hand, it might be a really good investment that could result in big benefits. With this in mind, a few ideas are suggested below.

i) A truly fundamental issue is that of the polarity differences observed at positive and negative brushes. The comments by Dr. Lynch were very interesting but I don't think they tell the whole story, since pronounced polarity differences were observed in the UK with silver slip-rings and silver –plated carbon fibers in reducing atmospheres. Polarity differences have also been observed with conventional silver-graphite brushes. A study of this phenomenon using modern diagnostic techniques would be very worthwhile. I recommend that some discussions be held with the folks at NRL – they were involved in the Westinghouse/ONR program of more than twenty years ago and they possess some excellent diagnostic capabilities (*which we are accessing under the railgun program*). An essential part of this study should be to evaluate additives to the atmosphere. In addition to water vapor, long chain hydrocarbons have also been shown to be effective (and in smaller concentrations that water).

ii) On the development side, my view is that the whole design of the brush region should be revisited before committing to the same design for the full-scale machine. I am not convinced that the present design is the best use of the available space. Part of this study might involve the study of forces on the brush box fixture and an evaluation of how to better manage those forces. (*As I mentioned, one of our analysts here at the IAT has started to develop a time-dependent magnetic model of the GA machine that could contribute to this study – however, I have stopped that activity at present since it is outside the scope of my present involvement for you.)*[8]

iii) It would be useful to obtain data on the relative contributions of frictional losses and electrical losses in the brush operation. As I said at the meeting, my own preference is to operate somewhat on the higher pressure side of the total loss minimum. It would be nice to have this data.

[8] This work, Dr. Dr Kuo-Ta Hsieh, has now been recognized as being useful to this effort and is the subject of a separate recent Grant by ONR.

A related issue is that I am concerned about the role of possible "stiction" (=stick-slip friction) in the control of such a low pressure brush system. Perhaps the most important aspect of the brush control system is to ensure that brushes do not lift off the surface of the slipring while carrying current. If they do, it is possible that sparking or arcing can occur, leading to slipring damage (including roughness) that will deleteriously affect the long term brush wear.

iv) I believe that all of the wear data presented so far has been in the absence of a magnetic field. Data in a field should be obtained and I see that that is the present plan.

4. Separate comments.

4.1. I am surprised that there cannot be an open discussion about the HiPerCon brushes. The success of the whole development program depends on the machine output power going through the sliding contact region. If it doesn't work or there are economic or technical difficulties, ONR and the Navy need to be able to discuss it openly with their stable of experts. ONR needs to consider how an open discussion can be initiated. (As a comment, it is also surprising to me that Noesis used Navy test rigs to get HiPerCon brush data under a Navy SBIR – but then the Navy is not allowed to see the data.)

4.2. Brush costs are an issue, as raised by Howard. Total brush holder cost is $250. Brushes are $100 each, so the total is $450. There are 16,000 brushes and half the number of brush holders so total cost is 8000 x $450 = $3.6M. This seems to be an extraordinarily high number. Is my math correct? If this is true, it seems to reinforce the need to get alternative brush system designs and alternative brush suppliers.

4.3. If it would be helpful, I can discuss the possibility of setting up a documentation center for current collection and homopolar generator topics at the University of Texas (IAT) on your behalf with our IAT Librarian. In discussions last week, the librarian indicated that he would be happy to do this. I recommend an electronic library in which available documents are scanned and put into a PDF format for electronic storage, with the original documents being retained by their present owners. This would be a good way for ONR to have a collection of all of the relevant data and would form a valuable reservoir of expertise – a lot of good work has been done in the past that is on the fringes of being lost to the community. This work could form a valuable guide as to future R&D directions for ONR. To cover any proprietary interests, specific documents could be limited as far as access and circulation are concerned.

4.4. If you are interested, there are a few people at the University of Texas that might be interested in helping with studies and one or two others that have experience in this area. Please let me know if you wish me to contact them with a possible view to helping.

4.5. Finally, I am a little bit serious about the idea of doing tests with fully superconducting brushes ("the ultimate brush"). Maybe this could be something to be tried experimentally with Shahin using HTSC wire cooled to liquid helium temperatures. If you are interested in this, I will talk to him and get back to you with some ideas.

APPENDIX C

Memo to: Ellie Martin (ONR); Will Creedon (GA); Howard Stevens (Anteon)
Subject: Notes from Quarterly HPM Review Meeting held on 14 April 2004
From: Ian McNab (IAT)
Date: 16 April 2004

1. Brushes

a) Obviously a lot of good work has been done by ZiBi and the team – but there is still a long way to go.
b) Having more test rigs is good, especially if magnetic fields are present.
c) Increasing the number of brushes will likely make things worse, rather than better. If we are correct in thinking that a thin (monomolecular?) layer of moisture on the surface of the slipring is necessary, control over the moisture level of the CO_2 will be required.
d) Having Neal Sondergaard and Bill Lynch involved in ongoing research in this area is a good thing and I would like to stay involved in what they do. It is not yet clear to me that the liquid solutions that Bill is discussing will be capable of transferring the current densities needed via ionic conduction – but it is worth trying.

2. Slipring

a) Don't forget to think about making measurements of slipring wear – this will become increasingly important as the brush coverage increases.

3. Full-scale machine design

a) Make sure that Niles and the design team provide as much space as possible for the brushes.
b) Rethink the brush-holder design to reduce the space claim – I think this will have a big effect on the total machine size but the brush designers will always benefit from more space, so this is a trade-off.
c) I am a bit concerned about the fabrication techniques for the rotor cylinders and sliprings. I discussed this with Niles and he seems to have thought about this a lot but it still seems to be a critical area. For example, if a shrink fit is used to attach the sliprings to the cylinders and there are some regions of poor electrical contact, this could introduce a distortion in the current flow though the brushes (circumferentially). Good assembly procedures, building and proving mock-ups and introducing QA procedures to confirm the electrical quality of these joins are important.

4. Subscale Machine

a) The present testing program schedule seems very compressed and optimistic to me. I would be very surprised if all the tasks can be accomplished in the time allowed.
b) It would be nice if continued testing could take place after the end of the present schedule. You have all invested a lot of time and effort in building the machine – it would seem sensible to keep the testing going to establish long term performance and evaluate excursions in the operating envelope.

ONR Homopolar Brush IPT

Cont rials P ce

Presented by
Dr. Chadee Persad
Senior Research Scientist, The University of Texas (IAT)
ONR Homopolar Brush IPT Meeting, Arlington, VA.
30 November 2004

Talk 1104 persad 1

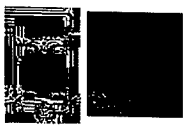
Outline of Today's Talk

- *A. Homopolar Generator (HPG) Work at Utexas*
- *B. Better Brushes for Pulsed HPG*
- *C. Better Materials for Solid Armature Railguns*
- *D. Better Materials for Rail Conductors*
- *E. HPM Fiber Brushes - Forensics and Expts*
- *F. Next Steps toward Better HPM Brushes*

Talk 1104 persad 2

HEME: Two surfaces interacting

Pin-on-Disk Tester



Sliding Contact AND High Current

IMAGE CREDIT: www.bccdc.org/images/ site/rps/tabletamp.gif

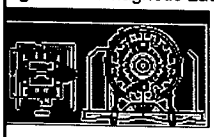
plus

E and B Fields & Environment Species

Talk 1104 persad 3

A. Homopolar Generator (HPG) Work at the University of Texas Center for Electromechanics

Homopolar Generator Research initiated c1970 has blossomed into a range of Pulsed Power Research activities - eg Electromagnetic Launchers ***and*** Solid State Switching



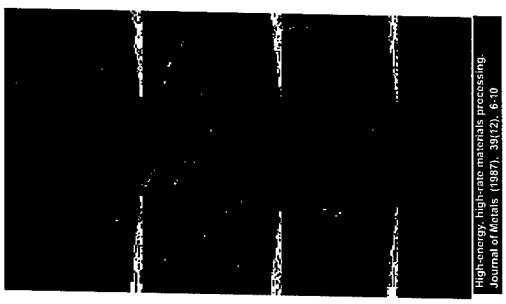
Lead Investigators in these efforts include:

H. G. Rylander, H. H. Woodson, W. F. Weldon, and R. Hebner

IMAGE CREDITS: Images on this slide were taken from University of Texas Center for Electromechanics Photo Archives

Talk 1104 persad 4

Molybdenum powders were consolidated in one second using a high current discharge from the UTX 10 MJ Homopolar Generator



High-energy, high-rate materials processing. Journal of Metals (1987), 39(12), 6-10

Powder ***Increasing Density (Energy Input) >>>*** Fully Dense Solid

Talk 1104 persad 5

B. Better Brushes for Pulsed HPG

I. Morganite CM1s: sliding velocities up to 160 m s-1
Powder Metallurgy product and current densities up to 870 A cm-2
Copper+Graphite+Lead/Tin Binder

II. Binderless Copper-Graphite
sliding velocities up to 160 m s-1
and current densities up to 870 A cm-2
Powder Metallurgy Product
Processed by Resistance Sintering

Examples of Published Research:

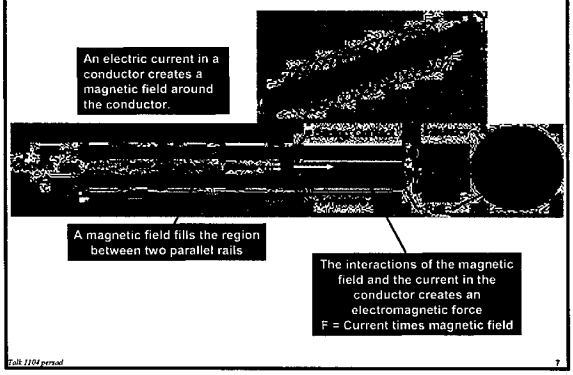
Tribological behavior of metal matrix composites
Wear, Volume 54, Issue 1, May 1979, Pages 175-185

Wear mechanism in composites: a qualitative model
Wear, Volume 51, Issue 1, November 1978, Pages 169-179

Friction and wear properties of two types of Copper — Graphite brushes under severe sliding *Wear, Volume 50, Issue 2, October 1978, Pages 371-381*

Talk 1104 persad 6

Basic Railgun Components

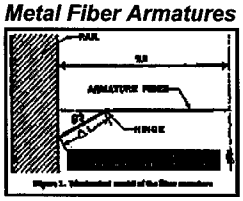


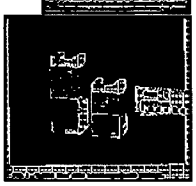
C. Better Materials for Solid Armature Railguns

I. Monolithic Armature Contacts

II. Divided Armature Contacts

III. Metal Fiber Armatures





Better Materials for Rail Conductors

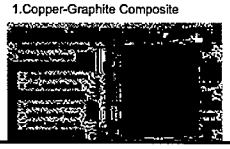
I. Commercial Copper Alloys- Monolithic
II. Bimetallic Constructions - Core & Overlay

Molybdenum Overlay

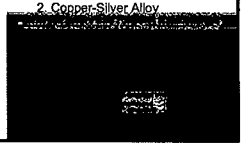
Hard Refractory Metal Overlays (eg Nb; Mo;W) were explosively bonded to conductive copper cores

III. Developmental Materials

1.Copper-Graphite Composite

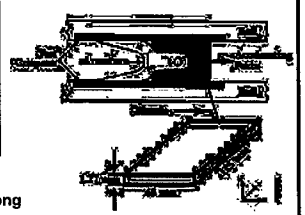


2. Copper-Silver Alloy



Experimental Testbed

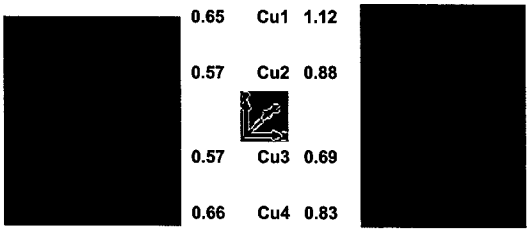
IAT Electromagnetic Launch Facility



- **40 mm square bore, 7 m long**
- **7075-T6 Aluminum alloy armature, 165 g**
- **Test coupon: 125mm x 45 mm x 1.27mm**
- **Traverse velocity: 0 - 400 m/s**
- **Peak current: 950kA**

Post Test Hardness

Vickers Hardness (Gpa), 25g load



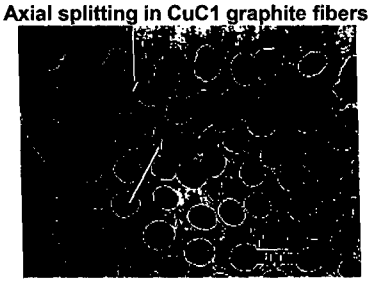
- **Increase in hardness of all Cu metal layers**

Flow in Cu Metal Layer and Composite Layer

- **Top layer matrix flow in x-direction**
- **Cracks along high fiber density path**
- **Matrix voids at fiber periphery**
- **Matrix squeeze-out (fiber-to-fiber contact)**
- **Graphite fiber cracking**

Axial Splitting

Axial splitting in CuC1 graphite fibers



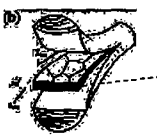
SEM photomicrograph of damaged area

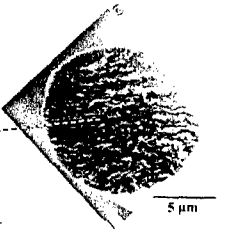
Talk 1104 persad 13

C Fiber Damage Mechanism

Schematic orientation of graphite planes

SEM image of P100 pitch fiber showing graphitic layers in fractured cross-section





Schematic sheet structure orientation of graphite in fiber that allows easy shear

E. J. Roche, Electron Microscopy study of mesophase pitch-based graphite fibers, J. Materials Science, 25, 2149 (1990)
M. Endo et al, Structural characterization of milled mesophase pitch-based carbon fibers, Carbon, 36, 11, (1998)

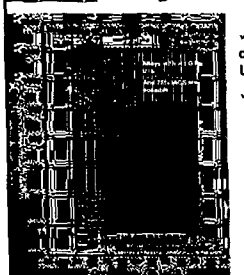
Talk 1104 persad 14

Conclusions

- Large deformation stresses in all-copper layers produce noticeable flow and thinning
- Hardness increase in all four Cu metal layers
- Damage in concentrated in contacting layer and in composite layer immediately below contact layer
- Damage in form of continuous cracks with preferred shear orientation
- Potential use of P100 fibers with low shear strength as sensors for local strains, flow in MMC subjected to complex loading

Talk 1104 persad 15

CuAg Conductor Development



✓High strength and high electrical conductivity (Combination of 1000 M Pa UTS, and >75% IACS)

✓Evaluation In Progress

- Testing of high quality material
- 3 inserts w/ different thicknesses
- Current maximum 1000 kA

NOTE: This alloy has been used in high field magnets operated at RT. It has properties that would make it a good HPM brush.

16

Talk 1104 persad 16

E. HPM Fiber Brushes - Forensics and Experiments

I. Previous Work - Lit & Pat Search

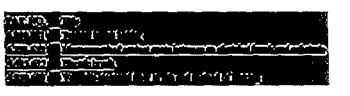
II. Field-Assisted Cu Corrosion Experiments

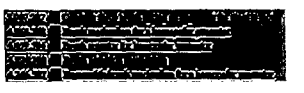
III. Preliminary Hypotheses

Talk 1104 persad 17

E. HPM Fiber Brushes - Forensics and Experiments

US Patent Search





United States Patent 4,415,635 *Wilsdorf*, et al. November 15, 1983

Electric *brush*

A multifiber electrical brush formed of an electrically conductive matrix material having plural electrically conducting fiber wires embedded therein and extending therefrom, wherein the fiber wires have a diameter varying from 1 to 120 mu.m, a length on the order of 100 times greater than the diameter thereof, and a packing density between 1-25% Suitable materials for the fiber wires are platinum, gold, silver, copper, palladium, or niobium which may be embedded in a copper, silver, or other suitable matrix material, or copper embedded in an aluminum matrix

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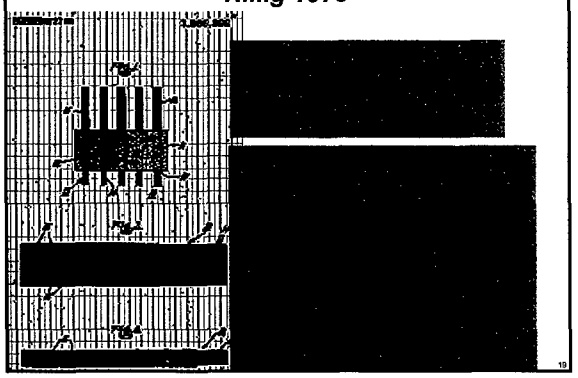
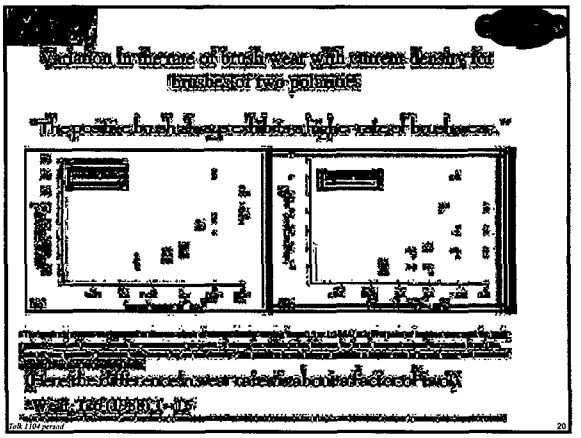
Brushmaking US Patent: Hillig 1975



19



Talk 1104 persad 20

Corrosion of Copper

Background

- **Atmospheric Corrosion**
  - **Oxidation**
- **Aqueous Corrosion**
  - **Fresh Water**
  - **Salt Water**

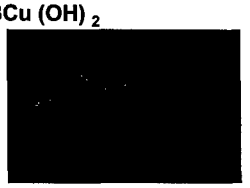
Statue of Liberty. Photo by Eileen Barroso

Talk 1104 persad 21

Chemistry of Corrosion Products in High Tension Wires of Electric Railway

Cu Electrical Conductors*

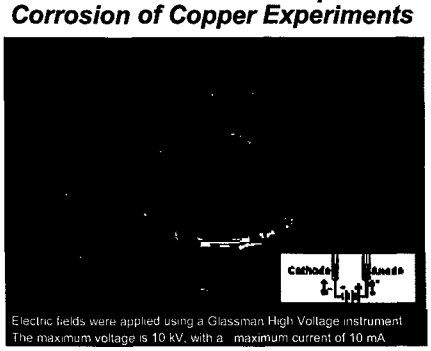
1. $CuCl_2$ - $3Cu(OH)_2$
2. $CuCO_3$
3. Cu_2O



* 1500V High Tension Wires of Japanese Electric Railway in Y. Aoyama, Werkstoffe Corrosion 12, p148 (1961)

Talk 1104 persad 22

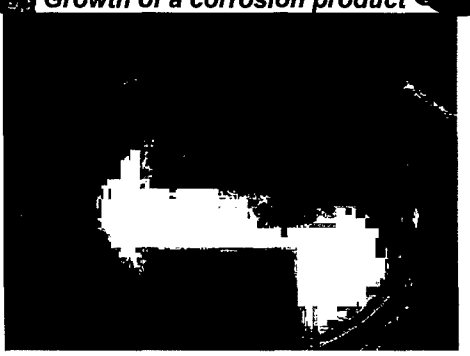
Apparatus Used for IAT Field-Assisted Aqueous Corrosion of Copper Experiments



Electric fields were applied using a Glassman High Voltage instrument
The maximum voltage is 10 kV, with a maximum current of 10 mA

Talk 1104 persad 23

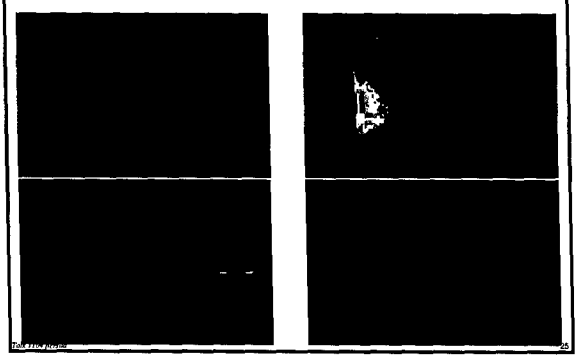
Growth of a corrosion product



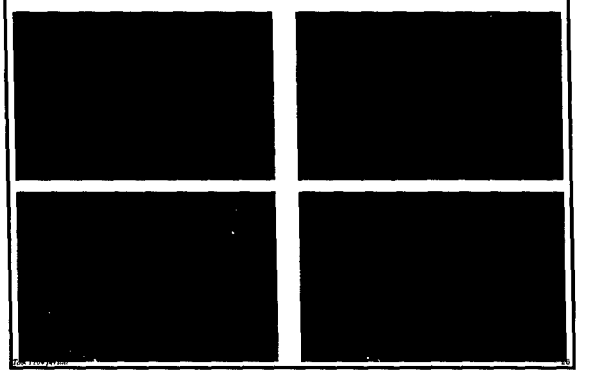
Voltage Gradient 500V/25mm, I=5 mA, t=300s

Talk 1104 persad 24

Up Growth Experiment #42

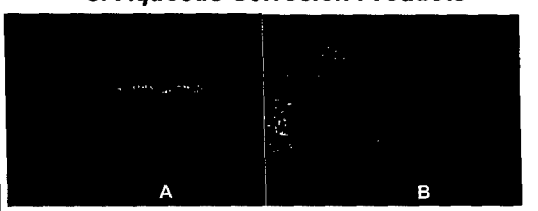


Circle Experiment #44



Measured rate of growth of corrosion products - 900s Tests

Analytical Electron Microscopy of Aqueous Corrosion Products



+Two different morphologies observed

A (Left) is fine - submicron-and feathery; B (Right) is globular ~ 5 micron

+Variation in chemical composition -

Cu & O in EDS of A (Left); Cu, C, & O in EDS of B (Right)

+Any similarities to wear debris from GA Nov 2003 Tests?

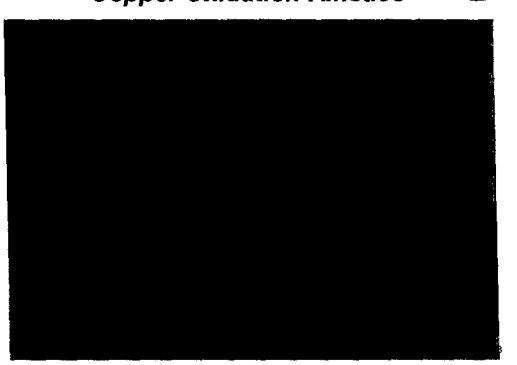
How to inhibit the oxidation of copper*

One way is to introduce a barrier layer at the surface that is impervious to the transport of either copper or oxygen. This is the mechanism that, for example, protects aluminum from extensive oxidation even though aluminum is intrinsically a very reactive metal. In the case of aluminum, it is the formation of a self-passivating barrier layer of aluminum oxide that stops further oxidation.

The second way to inhibit oxidation is to block the transport of Cu^+ ions through the Cu_2O. This is the mechanism that leads to the dramatic reduction in the oxidation rate of copper samples which have been ion implanted with B or Al** . In these cases, large effects are observed for total implants of less than one monolayer (i.e. 10^{15} atoms cm^{-3}). Mg additions to Cu can produce MgO surface barriers*.

* W.A. Lanford et al. /Materials Chemistry and Physics 41 (1995) 192-198
** P.J. Ding, W.A. Lanford, S. Hymes and S.P. Murarka, J. Appl. Phys., 74 (1993) 1331.

Copper Oxidation Kinetics



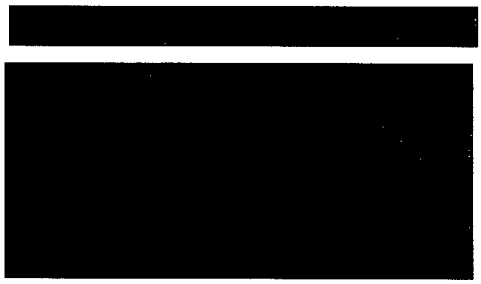
The Copper-Carbon Dioxide System*

- Negligible Cu-CO_2 reactivity at 300K up to 5 atmospheres [1].
- However, when Cu is partially covered with adsorbed O, a surface carbonate forms.
- The presence of CO_2 gas at a pressure as low as 0.05 mbar allows the retention of the carbonate up to 400K.

* Albert F. Carley et al, Surface oxygen and chemical specificity at copper and caesium surfaces, Faraday Discussions, 1996, 105, 225 -235

[1] P. B. Rasmussen et al, The interaction of carbon dioxide with Cu(100), Surface Science, Volumes 269-270 , 15 May 1992, Pages 352-359

Copper Carbonate Thermochemistry



The DTA curve shows a strong and sharp endothermic peak with a minimum at 575K

The TG curve indicates only one step for the process of thermal decomposition.

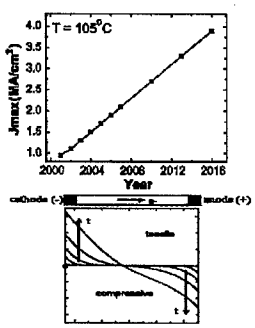
F. Next Steps toward Better HPM Brushes

I. Revisit Design - Model EM Loads (Space/Time)

II. Improve In-situ Measurements and Forensics

III. Capture lessons learned from GA & earlier tests, create hi-fi model of fiber /slip ring wear performance (+/-), then build and test better brushes

Electromigration Basics



- High current densities can cause the transport of mass in metals
- Occurs by transfer of momentum from electrons to positive metal ions
- Metal ions in some regions pile up and voids form in other regions
- Pileup can short-circuit adjacent conductors, whereas voids can result in open circuits

Source: Christine S. Hau-Riege, An introduction to Cu electromigration, Microelectronics Reliability, Volume 44, Issue 2 , Feb 2004, pp195-205

Rethink the Microbeam

Build a Wear Model- eg Use wear fragment mass and size distribution data

Rabinowicz* determined of the mass of wear fragments using auto-radiographic techniques. **The size distribution of copper wear fragments** transferred during sliding on mild steel was measured experimentally, and using these data the size distribution of the metallic junctions was calculated. The effect on the junctions of an increase of load was analyzed, and it was shown that the size of the largest junctions, and hence the mass of the largest wear particles, varied much less than does the applied load. In experiments of mild steel sliding on copper carried out to confirm these calculations, **the mass of the largest fragments was found to vary approximately as the 0.3 power of the load.**

E. Rabinowicz **Quantitative Study of the Wear,** 1953 *Proc. Phys. Soc. B* 66 929-936A **Issue 11 (November 1953)**

APPENDIX E. IAT Paper P.0742. 2004.

EXPERIMENTS ON THE OXIDATION OF COPPER IN AN ELECTRICAL FIELD

Eric Bierschenk
Institute for Advanced Technology
The University of Texas at Austin

Abstract—When copper is oxidized in high electric fields in an aqueous media, a fern-like growth phenomenon is observed. This fern-like growth starts at the cathode and grows toward the anode. Small, hair-like growths were also observed growing off the cathode. These hair-like growths were of small diameter (< 0.1 mm) and never exceeded more than 20 mm in length. To observe these phenomena, two copper terminals were placed in distilled water. Voltage was applied between the two terminals. In about 10 min, the fern-like growth appears directly beneath the cathode. All the experiments were conducted so as to observe and discover the factors determining the growth. Growth kinetics was controlled by field concentration, electrode geometry, and by time and temperature.

INTRODUCTION

Different experiments were conducted with multiple variations to further examine the properties surrounding the oxidation of copper in an electric field. All the experiments were conducted in an aqueous media to replicate selected conditions that conductors in a naval railgun would experience while at sea. Different variations include the presence of an electrolyte, the presence of a dielectric, differently shaped terminals, and differently shaped culture dishes. Electrical fields were applied using a Glassman High Voltage instrument. The maximum voltage obtainable on the apparatus is 10 kV, with a limiting factor of 10 mA of current. This same apparatus was used for every experiment, along with copper terminals. The immersed electrodes were varied.

EXPERIMENTS

Wider Dish. To study the extent to which the growth can persist, the initial experiment was conducted in a wider dish. The larger reaction cell also allows examination of other phenomena not observed when the experiment was conducted in the small dish. The terminals were placed 45 mm apart in a 150 mm Petri dish.

Results. The growth had reached 25 mm length within five minutes and continued to grow rather quickly. At 15 min, the growth had already reached the anode 45 mm away. A great number of particles were seen floating around the dish at about 60 min. These particles moved in a circular manner around the dish until they connected to the end of the fern-like growth; this was observed to be how the growth came about. After 210 min, a large leaf-like shape appeared between the two terminals. The structure was composed of many lines of debris, all flowing from the cathode toward the anode, as shown in Fig. 1. Upon completion of the experiment, after five hours there were distinct lines running between the terminals that filled the entire Petri dish. The lines grew in such a manner that it appeared as though they were following electric field lines.

Electric Field Tester. This experiment was conducted with one cathode and two anodes. The two anodes were situated on opposite sides of the Petri dish, and the cathode was placed directly between them. It was then predicted that the fern-like growth would form an hourglass shape, as shown in Figure 2, growing off the cathode and branching off toward the two anodes.

Results. Upon completion of the fern-like growth, 90 min, it was determined that the growth was almost identical to the predicted outcome, as shown in Fig. 3. The general shape was the same, but the actual lines observed in the previous experiment failed to appear. These findings prove that the growth follows the electric field lines.

Figure 1. The feather shape has completely reached the anode. Time: 210 minutes.

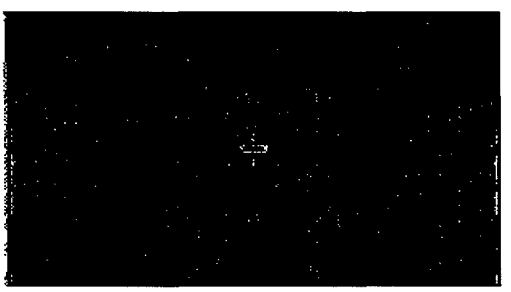


Figure 2. The predicted outcome for "Electric Field Tester."

Figure 3. Actual outcome for "Electric Field Tester." Time: 90 minutes.

Salt (Unmeasured Amounts). The presence of an electrolyte, sodium chloride, was predicted to have a new effect on the fern-like growth. It was previously unknown what the effect would be, but it was hypothesized that the rate of development of the fern-like growth would be faster.

Results. The salt had a surprising affect on the reaction. Not only did the fern-like growth not appear, but a new growth emerged. A milky blue cloud appeared around the anode, and a blue streak appeared off the cathode. This all took place within 25 min. The blue streak was then accompanied by a dark green, almost black, streak next to it. When the experiment was stopped at 150 min, the streak has gotten longer, as shown in Fig. 4, and the tip of the anode was yellow. This sample was then further analyzed with a scanning electron microscope (SEM). The green part of the streak was observed to be comprised of crystalline growths, as shown in Fig. 5, while the dark part of the streak was comprised of hexagonal-shaped growths, as shown in Fig. 6.

Salt (Measured Amounts). The previous experiment was replicated using the general formula

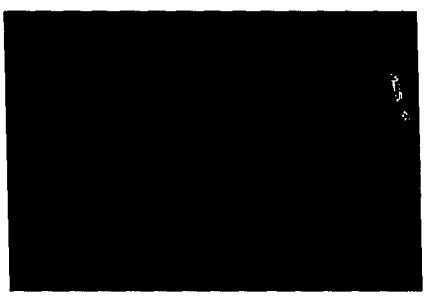


Figure 4. The bluish streak observed in "Salt: Measured Amounts." Time: 150 minutes.

Figure 5. SEM photograph of material from the green streak. Note the crystalline shape of the sample.

Figure 6. SEM photograph of material from the black streak. Note the hexagonal shape of the sample.

for artificial seawater, which is 2.4 g of sodium chloride for every 97.6 g of water. This was predicted to lower the resistance drastically and to speed up the reaction.

Results. The findings suggest that the presence of the salt actually slowed down the reaction, and it had a drastically different outcome than the previous salt experiment. The cathode began letting off bubbles at about 1 h. It took an entire 6 h before the reaction was complete. The water turned a turquoise blue color, with a few blotches of discoloring. Upon evaporation of the water, crystals were observed to be spread evenly on the bottom of the Petri dish, as shown in Fig.7. These crystals were shaped like salt crystals, but much larger.

Ferric Chloride. The presence of a new electrolyte, $FeCl_3$, was introduced to study the effect it would have on the reaction.

Results. A large collection of debris started to clump up around the cathode at only 2 min. Also, a yellow, nebula-shaped cloud appeared around the anode at this time. Toward the end of the experiment—at 90 min—debris was spread randomly in the dish, and the clump of debris on the cathode was significantly larger, as shown in Fig. 8. The portion of the anode that was immersed was also observed at this time to have turned white. After the evaporation of the water in the dish, about three days, a crystalline-like growth was observed on the bottom of the dish, as shown in Fig. 9. There were many small nucleation points for the crystals, which were spread randomly around in the Petri dish. Various other experiments were conducted on this matter, but they failed to provide any evidence for the reason these emerged.

Resistance/Time Ratio. This experiment was conducted to examine the relationship between the

Figure 7. A magnified photograph of the crystals left behind in "Salt (Measured Amounts)." Note the cathode in the photograph.

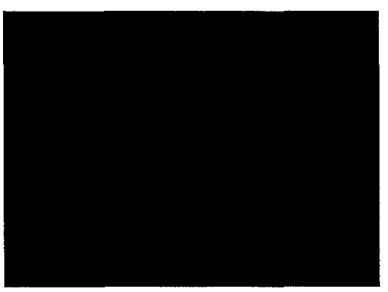


Figure 8. Photograph of the "Ferric Chloride" experiment. Note the clump of debris on the cathode.

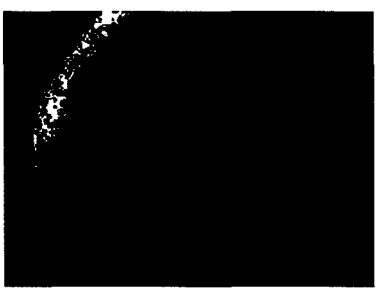
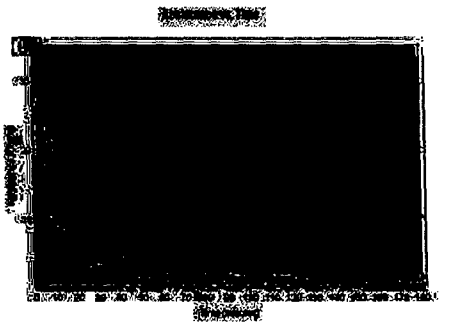


Figure 9. A magnified photograph of the crystals left behind in "Ferric Chloride." Note the many nucleation points.

resistance of the water and time. Resistance was measured over a span of 180 min and recorded every 10 min using the formula Volts = Current x Resistance. Voltage and current were given by the power source, allowing the resistance to be found easily.

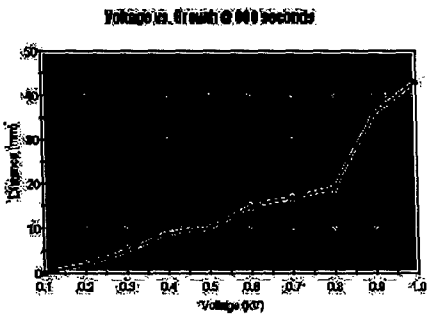
Results. Resistance, measured in Ohms, followed a downward trend, as shown in Graph 1. The resistance was as high as 35 Ω at the beginning and as low as .275 Ω at the end of the experiment. When the points are plotted, it appears as though the downward trend is an exponential progression.



Graph 1. Resistance/time ratio.

Voltage/Growth Ratio. In order to observe a relationship between the voltage and the rate of development of the fern-like growth, the following experiment was conducted. The expansion of the fern-like growth was measured in millimeters for varying voltages. The voltage varied between 0.1 kV and 1 kV, with the measurements taking place at 900 s for every specimen.

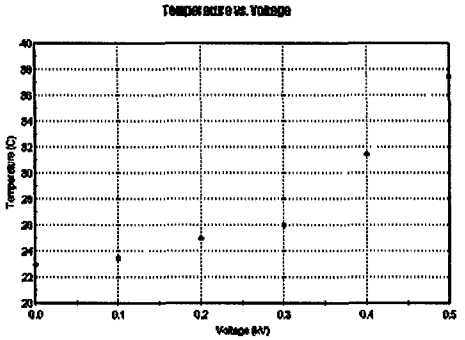
Results. By viewing the graph, one can conclude that the development of the fern-like growth is related to the voltage, as shown in Graph 2. The growth increases continuously for every increase in voltage. The growth spans between no growth for 0.1 kV and 43 mm for 1 kV.



Graph 2. Voltage/growth ratio.

Temperature/Voltage Ratio. This experiment was conducted to observe the relationship between the voltage and the temperature of the water. The voltage varied from 0.1 kV to 0.5 kV, and the temperature was taken at 600 s.

Results. The findings suggest that there is indeed a relationship between the voltage and the temperature of the water, as shown in Graph 3. The relationship suggested by the findings is an increase in temperature for every increase in voltage.



Graph 3. Temperature/voltage ratio.

Circle. In order to further study the electrode geometry of the reaction, the anode was shaped in a circle and situated around the cathode. This was done in a shallow Petri dish that was about one cm deep. The anode was also one cm wide, and it had a radius of ten centimeters. The cathode was rolled into a column and place directly in the middle of the circular anode.

Results. Just as predicted, the fern-like growth developed from the cathode in the middle out toward the anode, as shown in Figure 10. Within 90 min, the growth had several branches that had reached the anode. This experiment showed that the fern-like growth was capable of sustaining itself even when branching off in all different directions.

Figure 10. The outward growth observed in Circle.

Down Growth. This experiment was set up differently from the initial procedure to observe any three-dimensional effects not witnessed before. It was arranged in a deep cylindrical dish with the cathode on the top, and the anode was placed on the bottom. It was hypothesized that a 3D growth would develop from the cathode down toward the anode.

Results. Although the experiment took longer to materialize, a three-dimensional growth did emerge from the cathode at the top, developing toward the anode at the bottom, as shown in Fig. 11. The growth never did reach the anode, but it did reach a length of about 2 cm. These two-centimeter growths were coming off the cathode in all different directions, and they all grew toward the anode along spherical electric field lines. The experiment ran for four hours, and in

this time period, the water began to move in a 3D convective manner between the two terminals. Debris could be observed moving in the current, but it all slowly made its way either to attach to the growth or to rest on the bottom. At the end of the experiment, a quantity of the debris managed to make its way to the bottom, where it stayed. This experiment showed more than the previous experiment had shown with its circular-shaped anode. This experiment showed that the fern-like growth was able to hold itself together, even in three dimensions.

Figure 11. The three-dimensional growth observed in Down Growth. Note the debris movement in the water below the cathode.

Castor Oil. The presence of a dielectric, castor oil, was introduced to the experiment to observe what effects it would have on the reaction. It was hypothesized beforehand that the presence of a dielectric would slow, if not completely stop, the reaction. The solution was half water, half oil. The cathode was placed in the castor oil, and the anode was placed in the water.

Results. Upon turning on the power, the oil split in half and allowed the water to flow between the two terminals. At only 15 min, the water contained millions of bubbles that occupied the entire surface of the water. The origin of all the bubbles was the cathode, which began letting off bubbles at only 5 min. It took an entire hour for the fern-like growth to reach the anode, as shown in Fig. 12, which supports the original hypothesis that the dielectric would slow the reaction down.

Figure 12. The growth observed in Castor Oil. Note the splitting of the oil to allow the water to run between the two terminals.

Magnet. A magnet was introduced to the experiment to observe any effect it would have on the fern-like growth. It was theorized beforehand that the magnet would have either a push or a pull on the fern growth. In order to observe this properly, the magnet was placed directly beneath the Petri dish and offset to one side. This was done so that the metallic characteristics of the magnet would not have an affect on the reaction, and the magnet was offset to one side so that it would be easier to observe a push or a pull on the growth. The voltage was kept at 0.2 kV for the first 25 min and turned down to 0.05 kV for the remaining 95 min.

Results. The magnet did not appear to have an effect on the fern-like growth, as shown in Fig. 13. Even when the voltage was turned down to 0.5 kV, it did not have any affect at all. The growth emerged normally, and it reached the anode as usual.

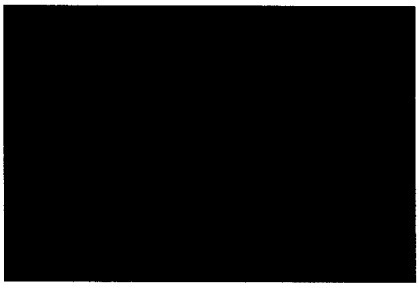


Figure 13. The growth observed in Magnet. Note the gold-colored magnet offset to the left. Also note that there is no effect on fern growth.

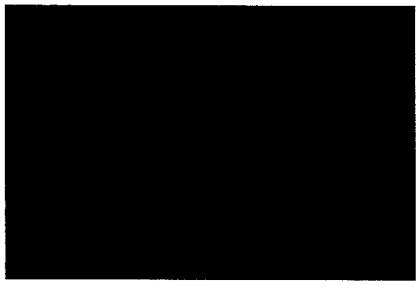


Figure 14. The growth observed in Teardrop. Note that the fern-like growth emerges from the rounded side of the teardrop-shaped copper piece and not from the pointed side.

Small Teardrop. A piece of copper was placed in the Petri dish along with the terminals to further study the electrode geometry. The piece of copper was cut into the shape of a teardrop, and it was placed in such a manner that the rounded side of the teardrop was closer to the anode than the pointed side. This was done because it had been observed previously that the fern-like growth favored sharp points for nucleation locations. The experiment was designed to show which the fern-like growth favored more, distance or a sharp point for a nucleation site.

Results. The fern-like growth emerged on the rounded side of the teardrop, which was the side closer to the anode, as shown in Fig. 14. These findings suggest that the distance between the anode and the copper piece plays a bigger role in determining nucleation sites than does the presence of a sharp point.

CONCLUSION

All the findings of the experiments suggest that there is still much to be discovered about the oxidation of copper in high electric fields. This series of experiments helps to further understand the factors controlling growth, field concentration, electrode geometry, and the effect of time and temperature on growth, but there is more to discover than can be observed through these experiments. Future experiments should be focused more on artificial seawater being used as the aqueous media, the direction that the Navy would like to go with research in this area. Further studies of the oxidation of copper in artificial seawater will help to find an efficient way to reduce corrosion and oxidation of copper for future naval railguns.

ACKNOWLEDGMENTS

Thank you to Martha Simmons and Reginald Jim Allen at the lab for their help with the experiments. A special thanks to Chadee Persad for his leadership and guidance.

APPENDIX F. Current Collection and Fiber Brushes
IAT Technical Note: IAT TN.0288

Author: Dr. Ian R. McNab
Date: 29 November 2004

Introduction

In addition to the references on fiber brushes provided recently by Dr. Chadee Persad to the ONR Workspace in connection with the Superconducting Homopolar Motor project, some papers in early Holm Conferences (published in the IEEE Transactions on Components, Hybrids and Manufacturing Technology) and the papers in the 1982 Volume Number 78 of WEAR may be relevant to these efforts.

DARPA/ONR/Westinghouse Current Collection research (1978-83)

Westinghouse Research Laboratories in Monroeville, PA had the primary contract from ONR for the development of current collection systems under an effort sponsored by the Materials Science Office of (D)ARPA[9]. The purpose was to develop current collection technology for homopolar machines for ship propulsion. While the Annapolis team of Tim Doyle, Howard Stevens, Dr. Neil Sondergaard and their colleagues were developing liquid metal current collection systems for their homopolar motor effort, Westinghouse, having investigated NaK systems (and I was part of this), concluded that liquid metals were inappropriate for ship use and turned to solid "brushes". Westinghouse initially looked at solid graphite and metal-graphite brushes, starting from the work done at Westinghouse (and GE) during WW II on the high altitude brush dusting problem for aircraft generators. As part of this, close connection existed between Westinghouse and their favored conventional brush supplier, the Stackpole Carbon Co. of St. Mary's, PA. Building on the work done in the Britain at IRD Co., (I was also involved in this) the emphasis turned to metal-plated fiber brushes. Richard Marshall from Australia also contributed some of his ideas to this work based on his experience with Morganite copper-graphite brushes on the 500 MJ Canberra homopolar generator. Westinghouse built a large number of brush test rigs to evaluate different brush concepts, including the MEBT (= Machine Environment Brush Tester), that is still in use today.

Much of the work reported was undertaken under the ONR Contract N00014-81-C-0464 with Westinghouse. I no longer have the detailed reports from that Contract but they may exist in ONR or DTIC.

Although Westinghouse had the main contract from ONR but an integral feature of the research approach we followed was the coordination with other government organizations, expert consultants and universities. The primary universities involved were MIT (Prof. Ernie Rabinowicz), Syracuse (Prof. Richard Vook), North Carolina State University (Prof. Ralph Burton and Dr. Michael Bryant), Carnegie Mellon University (Prof. William. Hughes), and the University of Virginia (Profs. Heinz and Doris Wilsdorf). Consultants included Dr. Brian Williamson (UK) and Dr. Charles Bronariek (Tuskagee Institute – previously Westinghouse).

Out of this work, and the earlier work in the UK that I reported at the Brush Workshop on 19 February 2004 came the interest in fiber and wire brushes that led to where we are today.

Holm Conferences

The annual Holm conferences provided a useful forum in which to meet and discuss the current collection work we were performing for ONR. The papers were given at these conferences are shown in

[9] At that time ARPA was used, now it is DARPA. Dr. Arden Bement was the head of the Materials Science Office and Dr. Mike Buckley was the Project Manager.

Table I. We deliberately introduced the concept of linked papers in which the studies for ONR were reported, as is evident from the paper titles.

Table I. Papers relating to the Westinghouse ONR Research Program

Holm Conference No.	IEEE Trans. Volume	Authors	Title
23rd. Chicago, IL. Nov. 1-3, 1977	***CHMT-1. March 1978***	I.R. McNab	Pulsed High Power Brush Research
		J.L. Johnson & L.E. Moberly	High Current Brushes, Part I: Effect of Brush and Ring Materials
		P.K. Lee & J.L. Johnson	High Current Brushes, Part II: Effects of Gases and Hydrocarbon Vapors
24th. Chicago. IL Sept. 1978	***CHMT-2. March 1979***	I.R. McNab & J.L. Johnson	High Current Brushes, Part III: Performance Evaluation for Sintered Silver- Graphite Grades
		P. Reichner & O.S. Taylor	Shunts for High-Current Density Brushes
		O.S.Taylor & P. Reichner	Mechanical Load Aspects of High Current Brush System Design
		R.A. Marshall & R.M. Slepian	Pulsed High Power Brush research, Part III: Experiments at 15.5 MA/m^2 and 277 m/s.
25th. Chicago, IL Sept. 1979	***CHMT-3. March 1980***	P.K. Lee	High-Current Brush Material development, Part 1: Sintered Metal-Coated Graphite.
		R.W. Vook, et al.	Elemental Surface Composition of Slip Ring Copper as a Function of Temperature.
		P. Reichner	Metallic Brushes for Extreme High Current Applications.
		I.R. McNab & W.R. Gass	High Current Density Carbon Fiber Brush experiments in Humidified Air and Helium.
		J.L. Johnson & O.S. Taylor	High Current Brushes, Part IV: Machine Environment Tests
		S. Dillich & D. K-Wilsdorf.	Effects of Surface Films on the Performance of Silver Graphite Electric Brushes.
		R.M. Slepian	High Current Brushes, Part V: Subdivided Monolithic Brushes at Very High Current Levels.
		J. Schreurs, J.L. Johnson & I.R. McNab	High Current Brushes, part VI: Evaluation of Slip Ring Surface Films.
26th, Chicago. IL Sept 29-Oct 1, 1980.	***CHMT-4. March 1981***	P. Reichner	High Current Tests of Metal Fiber Brushes
		J. Schreurs, J.L. Johnson & I.R. McNab	Characterization of Thick Films formed on Slip Rings during High Current Density Operation
		B. Singh & R.W. Vook	*In Situ* AES Characterization of Rotating Electrical Contacts
		P. Reichner	Pressure-Wear Theory for Sliding Electric Contacts
		P.K. Lee	High Current Brush material Development, Part II: Metal-Solid Lubricant Coated Wires
		R.A. Marshall	High Current & High Current Density Pulse Tests of Brushes and Collectors for Homopolar Energy Stores.

1981 Current Collection Conference

In 1981, it was decided that interest in current collection for electric machines was at a sufficient level that it might be useful to hold a special conference dedicated solely to that topic. Accordingly, a conference was arranged to be held in Chicago on Sept 23-25, 1981. The Conference was co-sponsored by the Westinghouse Research Laboratories and by ONR and I acted as conference chairman. Volume Number 78 of Wear was set aside to cover the Proceedings of this Current Collection Conference and it was also published by Elsevier Sequoia as a separate volume (ISBN 0-444-75011-8) in 1982. Only a few copies of this volume were made - mostly for the 50 or so attendees. I still have a couple of these and our library obtained one on-line from eBay (or similar) a few months ago that belonged to a former Westinghouse employee (Owen Taylor).

I provided the Foreword to the volume and that is attached here as an Acrobat file, together with the Index to the volume.

Fiber Brushes in Railguns

The early use of fiber brushes as armatures in railguns was initially done by the same Westinghouse researchers and for the same reasons - they offered good electrical contact under stressing conditions of acceleration and current. The initial tests were done in a small (10mm x 10 mm square bore railgun, called ELF) and reported by David Ross and Dan Deis at the 1st Electromagnetic Launcher Symposium in San Diego in November 1980[10]. Later (and noted as a footnote to the Foreword in the Wear volume) we used a larger fiber bundle in the 50 mm x 50 mm square bore EMACK system during tests in January 1982 and achieved very high velocities. After this system was delivered to the Army ARDEC Laboratories in Picatinny, NJ Army the same technology was used there. One of the Westinghouse engineers, Dr. Gerry Ferrentino moved to work at ARDEC and, together with Hans Kolkurt from TNO in the Netherlands, who came there as an exchange person in 1984, picked up this technology and developed it further. The Dutch and TNO are no longer working on electric guns but the residue of this interest now lies with the French group at the Institute Saint Louis in France, where several variants of the fiber brush technology have been tested in their EM guns and research is still continuing. Most of that work has been reported in the twelve International EM Launcher Symposia, the proceedings of which have been published in the IEEE Transactions on Magnetics from 1982 to 2005.

Fiber Brush Patents

As the start of a data base on patents that ONR might wish to assemble, I have attached here a list of patents relating to brushes and current collection that I know about. This is embarrassingly "McNab-centric" at present but only because I have not had time to add other patents that I know exist. I know that Dr. Persad and many of you have many more. I certainly have more in my files and will find them and add to the list. Copies of three of the patents are also attached here as PDF files. Some of the names mentioned here could provide a useful basis for a patent search.

Where are they now?

Much of the work discussed above was performed twenty or more years ago. One might ask where these folks are now. In some cases, there are sad answers (Tony Appleton died ten years ago, Jan Schreurs died in his early 50's). Many have retired: Phil Reichner (in the Pittsburgh area); Geoff Wilkin (in Northumberland, UK); Dick Marshall (in Austin). I have lost touch with many of the Westinghouse researchers (Larry Moberly, Johnny Johnson, P. K. Lee). Some have moved on and are no longer interested in this field (e.g., Owen Taylor). Fortunately, a few, such as Professor Michael Bryant[11], are still around and are still interested in this field.

[10] Included in the Proceedings of that conference published by the IEEE in the Trans. Mag, January 1982.
[11] Now at UT Austin.

Patents

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Foreword

Advances in electrical current collection

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(Received December 1, 1981)

During the last decade, substantial advances have taken place in several areas of technology concerned with the transfer of electrical current across sliding interfaces. The requirement to transfer current from moving metal surfaces to sliding conductors is essential for many electrical machines, and research in this field goes back to the earliest days of the electrical industry.

In recent years several advanced rotating and linear electrical machine concepts have been developed which depend for their success on the efficient transfer of current across sliding interfaces. For example, the steady state operation of brushes at 8 MA m^{-2} is the goal for advanced land or sea propulsion machinery. Even higher current densities (18 MA m^{-2}) and speeds (300 m s^{-1}) are required for the subsecond operation of inertial storage pulsed power sources. Speeds and current densities more than an order of magnitude higher, although for millisecond pulses, may prove to be necessary for linear electromagnetic projectile accelerators. In all these cases the requirement for the efficient transfer of electrical current complicates the frictional and wear effects that take place at mechanically contacting sliding interfaces.

In the U.S.A. the major research and development efforts during the last few years have been centered on the David Taylor Naval Ship Research and Development Center, Annapolis, MD, and at Westinghouse Research and Development Center, Pittsburgh, PA. The former effort focused on the use of liquid metal techniques while the research of the Westinghouse scientists, and their colleagues in associated universities, has been concentrated on solid or multielement brush techniques. The Westinghouse program was supported by the Materials Science Office of the Advanced Research Projects Agency of the U.S. Department of Defense (DARPA) and monitored by the Office of Naval Research (ONR). Throughout the program regular Workshop meetings were held to enable the contributing researchers to meet and exchange information. However, since attendance at these Workshops was limited and the proceedings were not published, it was decided to hold a full International Conference at which a combination of researchers, manufacturers and

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users could interact to discuss the recent advances in this field. This conference, cosponsored by the Office of Naval Research and by Westinghouse Electric Corporation, was held in Chicago on September 23 - 25, 1981. Although relatively small in numbers, with approximately 60 attendees, the Conference brought together active experts in this field from the U.S.A., Canada, France, Gt. Britain and China, and two papers were submitted from the U.S.S.R. In view of the difficulties inherent in this subject it is likely that the combined efforts of these international experts with their spectrum of research and industrial perspectives will be needed to enable further progress in this subject to be made.

Substantial advances in liquid metal current collection techniques have been made during the last decade under the auspices of the U.S. Navy program. The work reported here shows that the use of the "narrow gap" collector geometry, based on the use of surface tension effects in a metallic braid that is virtually in touching contact with the rotor surface, enables the problems associated with liquid metal expulsion as a result of the $J \times B$ forces to be solved, and long term stable operation has been demonstrated. The major problem with liquid metals is the choice of fluids available, most of which have significant disadvantages. Sodium and potassium and their alloys (Na–K) are very reactive chemically while mercury is toxic and Ga–In alloys form contact-disrupting black powder oxides in oxygen-containing atmospheres. Despite the excellent performance observed in carefully controlled laboratory conditions, these considerations are likely to limit the practical use of liquid metals. Some work reported in this meeting was therefore devoted to discovering whether less reactive liquid metals, such as low melting point alloys, can be used for this application.

In most electrical machinery at present in operation, the current transfer function is provided by carbon-based brushes supplied by the brush industry. In most cases the operation of such brushes is limited by a current density–speed–wear loss envelope for which typical current densities and speeds are 0.2 MA m^{-2} and 40 m s^{-1}. Evaluation of the reasons for these limitations shows that the primary cause is the build-up of a complex film, mainly cuprous oxide, on the surface of the slip ring or commutator. In addition, the choice of the carbon-based brush is generally mandated by the requirement to develop a high voltage to force the current to flow into a new circuit, *i.e.* to commutate. For some of the new machine applications mentioned above, the commutation function may not exist, or may be less arduous, thereby opening the way to other brush concepts or materials.

As reported here, the work under the DARPA–ONR–Westinghouse program has shown that solid or monolithic brushes made from relatively conventional materials can be operated up to much higher current densities and speeds than previously considered possible provided that (i) careful atmosphere control (non-air) is provided, (ii) brush and environment temperatures are controlled, (iii) adequate mechanical control is maintained and (iv) optimal materials are chosen. Under these conditions several remarkable advances have taken place in recent years.

(i) Multiple brush assemblies have been operated continuously in machines at current densities in excess of 1.5 MA m^{-2} at 40 m s^{-1}.

(ii) Individual brushes have been operated in steady state conditions to current densities of 6 MA m^{-2} at 15 m s^{-1}.

(iii) Multiple brush assemblies have been pulsed to more than 3 MA m^{-2} at 40 m s^{-1}.

(iv) Prototypic multiple brush modules have been pulsed at current densities of 18 MA m^{-2} for periods of 0.25 s with simultaneous speeds up to 280 m s^{-1}.

Supporting these practical advances has been a wide range of fundamental studies into materials and surface physics at Westinghouse and in associated universities. These studies have encompassed aspects such as the following.

(i) Advanced diagnostic techniques (scanning electron microscopy, Auger analysis etc.) are used to determine the physical state of the materials.

(ii) Theoretical and practical studies on the electrical and mechanical effects taking place at the sliding interfaces are carried out.

(iii) Evaluations are made of materials compatibility and interactions.

(iv) New wear models are developed.

(v) The mechanical conditions imposed by practical materials and engineering limits and their effects on the sliding contact process are evaluated.

While much has been learned, and is reported in this volume, it is clear that these investigations are far from complete and that more remains to be done if we are to reach the goal of a unified theory to explain sliding contact behavior.

An alternative to the use of liquid metals or monolithic blocks of carbon, or metal–carbon, is the multielement contact which in its most common form may utilize the "fiber" brush. Much of the early work in this area was based on the development of carbon fibers in the 1960s when it was realized by researchers in Gt. Britain that this technology would permit a flexible carbon brush having multiple independent contacts to be made. This has been found to have some application in a modified form as the fringe fiber brush for machines operating in an arduous environment as described in two papers in this volume. However, for applications where low contact voltage drops were required, it was found to be beneficial to provide a coating on each individual fiber, for example by electroplating, to provide a high conductivity sheath on the high strength fiber. Although brushes have been successfully manufactured in this way, studies during the Westinghouse program showed that the optimum performance may not require as many contacts as provided by the standard 8 μm diameter carbon fibers. Consequently, new metal fiber brushes have been developed, with typical fiber diameters of 125 μm. Experiments with these brushes have been very successful showing, for example, continuous operation at very high current densities (greater than 10 MA m^{-2}) with very low losses and wear. An interesting feature of this work has been that independent groups have

followed similar lines, with similar results. This technology has been applied to the pulsed homopolar machine at the Naval Research Laboratory and has shown successful operation at sliding speeds up to 475 m s^{-1}, which is believed to be the highest peripheral speed achieved with sliding contacts in rotational machinery.

This same technology has also been applied to the problems found in switch ring machines, and results obtained with a combined metal–carbon plus metal fiber brush are described in a paper in this meeting. With this technology, current densities of 1.5 MA m^{-2} were achieved on a continuous basis. Although still at an early stage, this technology may represent the next step in commutation technology after the carbon fiber fringe brush.

Probably the ultimate sliding contact operation is represented by the conditions which exist in linear electromagnetic projectile accelerators. In such systems extremely high current densities (of the order of gigaamperes per meter squared) have to be transferred at very high speeds (of the order of kilometers per second or more). The only feature that makes such a contact feasible is its transient nature, usually of the order of a thousandth of a second. Nevertheless, conditions in such contacts are very severe and generally approach melting of the contacts. Research in this field is at a very early stage but some experimental work is reported here, together with factors that influence the successful operation, including electromagnetic transient effects. (See note added in proof.)

In summary, the work reported here provides a cross section of progress in this field which has traditionally shown relatively slow growth but where several important advances have been made in the last decade. Many of these advances have resulted from the DARPA–ONR program and I should like to take this opportunity to thank the Department of Defense program managers for their advice and encouragement throughout this program, especially A. Bement and M. R. Buckley of DARPA, and R. Seng, R. A. Burton and H. B. Martin of ONR. The financial support offered by the ONR and Westinghouse Electric Corporation that made this conference possible is gratefully acknowledged. In addition, I should like to express my appreciation of the help and advice offered in connection with the organization of this conference by R. E. Armington, Chairman of the Holm Conference.

Finally, I should like to thank all the authors and participants for making this a pleasant and rewarding meeting, and D. J. DiCesare for her secretarial help in organizing the meeting.

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Note added in proof. A fiber brush projectile has recently been accelerated to over 4 km s^{-1} while it transferred a current of more than 2 MA.

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(19) (CA) # CANADIAN PATENT

(54) ## CURRENT TRANSFER BRUSHES

(70) Wilkin, Geoffrey A. and McNab, Ian R., Fossway, Newcastle-upon-Tyne NE6 2YD, England

Granted to International Research & Development Company Limited, Fossway, Newcastle-upon-Tyne NE6 2YD, England

(21) APPLICATION No. 164,418
(22) FILED Feb. 23, 1973

(30) PRIORITY DATE Feb. 29, 1972 (9256/72) G. B.

No. OF CLAIMS 6 - No drawing

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ABSTRACT OF THE DISCLOSURE.

A current transfer brush is composed of refractory fibres, preferably high strength carbon fibres, with a metallic coating on the fibres which is composed of an under layer of a first metal and an over layer of a second metal. The over layer is of a highly conductive material such as silver and the under layer which improves coherence and adhesion of the over layer and thereby produces a very low brush voltage drop, is of a material such as nickel.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A current transfer brush comprising refractory fibres individually coated with a coating comprising an under layer composed of a metal selected from the group comprising titanium, vanadium, tantalum, chromium, molybdenum, tungsten, manganese, iron, cobalt, nickel and boron, and an overlayer of a second metal with high electrical conductivity which adheres to the under layer.

2. A current transfer brush as claimed in claim 1 in which the over layer is of silver.

3. A current transfer brush as claimed in claim 1 in which the over layer is selected from the group comprising silver, gold, copper, aluminium, cadmium and zinc.

4. A current transfer brush comprising refractory fibres each of which is coated with an under layer of a metal selected from chromium, iron, cobalt, and nickel and an over layer of a metal selected from silver, gold, copper, and alloys of silver and copper.

5. A current transfer brush as claimed in claim 4 in which the fibres are carbon fibres.

6. A current transfer brush as claimed in claim 5 in which the under layer is of nickel and the over layer is of silver.

*

A

The present invention relates to current transfer brushes consisting of refractory fibres, such as carbon fibres, coated with an electrically-conductive metallic layer.

Such brushes form the subject of British Patent No. 1,191,234 granted to International Research & Development Co. Ltd. on the 9th September, 1970 and U.S. Patent No. 3,668,451 granted to International Research & Development Co. Ltd. on 6th June, 1972 and are particularly valuable for use in homopolar machines where high speeds of rotation and large currents call for brushes which exhibit a low rate of wear when rubbing against a rapidly moving contact surface and which have high electrical conductivity. In these prior brushes the carbon fibres which are employed have very good mechanical properties because of their special method of production and they provide support for the layer of electrically-conductive metal, such as silver, which probably carries most of the current. The thickness of the layer is limited because it is essential to maintain the flexibility of the fibre in order to give satisfactory wear rates. Therefore the electrical conductivity cannot be increased simply by using a thicker coating. Unfortunately it is found in practice that a layer of a particular thickness, calculated from the weight deposited per unit area, gives a conductivity lower by a factor of 10 or more than the expected value. Moreover the conductivity, and thus the voltage drop at the brush, varies from one sample to another and is different according to whether the brush

is connected as a negative brush (from which electrons flow into the contact surface) or a positive brush (into which electrons flow from the contact surface).

The problem underlying the invention, therefore, is to improve the electrical properties of metal-coated fibre brushes without harming their mechanical properties and thereby suffering from increased wear rates. In accordance with the invention the solution to this problem is found in the provision of a brush composed of refractory fibres each of which has a metal coating composed of two layers of which the under layer is a homogeneous layer with a smooth surface while the outer layer is of high electrical conductivity, forms a homogeneous coating on the under layer, and has a high ionic mobility giving it the capacity for rapid diffusion across the surface of the under layer to fill cracks which may occur during operation.

It is believed that the formation of a satisfactory underlayer with good adhesion to a carbon fibre may require the formation of a thin carbide phase between the fibre and the underlayer. Hence the metals to be used for the underlayer are those with reasonably stable carbides namely titanium, vanadium, tantalum, chromium, molybdenum, tungsten, manganese, iron, cobalt, nickel, and boron. Of these the preferred materials are chromium, iron, cobalt, and nickel.

For the outer layer silver is the preferred material

because of its high electrical conductivity and its resistance to oxidation. Gold also has suitable properties but is unlikely to be used because of its high cost. If the brushes are to be run in a reducing atmosphere, thereby avoiding the risk of oxidation, it is possible to use copper, aluminium, cadmium or zinc, copper being preferred. It is also possible to use an alloy of silver and copper.

With a two-layer coating it has proved possible, for a coating of the same overall thickness, to obtain higher conductivity, i.e. lower voltage drop, than is possible with a single layer of either of the coating materials. This voltage drop is less variable from sample to sample and is less dependent on the direction of current flow between the brush and the contact surface. Moreover these results are obtained without any deterioration in the wear rate, in fact at high current densities there is even some reduction in the rate of wear, perhaps resulting from improved adhesion of the outer layer to the under layer under conditions of high thermal stress as compared with the adhesion of the material of the outer layer to the surface of the fibre.

A variety of deposition processes can be used for applying the two layers to the refractory fibres. The preferred process is that of electro-plating and details of how this may be applied are given in British Patent

Specifications Nos. 1,272,777 granted 30th August, 1972 and 1,309,252 granted 4th July, 1973, both to International Research & Development Co. Ltd. Other processes available include pyrolysis of an organo-metallic vapour, high vacuum evaporation, sputtering, and electroless plating (that is chemical reduction of metallic salts).

By way of example one embodiment of this invention will now be described in more detail and comparative information will be given to show how this embodiment with a two-layer coating affords substantially better results than a single layer of either of the coating materials separately. In this embodiment carbon fibres are coated with an under layer of nickel and an outer layer of silver.

The carbon fibres used are high strength fibres of RAE Type II produced as described in British Patent Specification No. 1,110,971 granted to National Research Development Corporation and published 24th April, 1968 by carbonization of polyacrylonitrile fibres while holding them under tension. The average diameter of the filaments is 7.5 μ m. When such filaments are electroplated with silver to give an average coating thickness, calculated in terms of the amount of metal deposited per unit length of a bundle consisting of as many as 10^4 fibres, of 1.0 μ m the electrical resistance is found to be 10 to 20 times higher than would be expected with a uniform layer of this thickness. This is thought to be due to the fact that the silver deposit is nodular and has areas of poor

adhesion to the carbon fibre.

If such carbon fibres are electroplated with nickel alone as a single layer a smoother, more homogeneous deposit is formed and the electrical properties are more consistent. There is better correlation between the calculated layer thickness and the actual conductivity but the overall voltage drop is generally higher than for a silver layer.

If now a silver layer is electroplated onto a nickel layer there is a marked improvement in the electrical and mechanical properties. Measurements of voltage drop made with brushes running at a speed of 35m/sec on a silver-plated slip ring with a current density of 500 KA/m^2 are given in the following table for the various types of brush

Fibre coating	Positive Brush	Negative Brush
Nickel	1.5	0.40
Silver	1.2	0.25
Silver on nickel	0.20	0.15

The average coating thickness, as calculated from the weight of material applied, was approximately 1 µ m for the silver layer alone, 0.7µm for the nickel layer alone, and 0.5 µ m of silver over 0.7µ m of nickel.

In the case of a nickel-coated positive brush the initial voltage drop was similar to that of a negative brush but within a few seconds of commencing operation it rose to the higher value given in the table.

It will be seen from the table that in addition to the low value of voltage drop obtained for a negative brush with a two-layer coating there is a very important improvement in the voltage drop for a positive brush so that the performance of the brush is largely independent of the direction of current flow.

A silver layer applied directly to the carbon fibre by electro-plating from an alkali cyanide bath is nodular and shows areas of poor adhesion where the material will readily flake off under mechanical stress. It is believed that the unevenness of the deposit and its lack of adhesion are responsible for the fact that the resistance per unit length is 10 to 20 times higher than would be expected from the calculated average layer thickness. A nickel layer plated from an acid bath gives a more smooth and homogeneous layer which despite the presence of longitudinal cracks showed little tendency to flake off. The correlation between resistance and calculated layer thickness was better than with silver.

When silver is plated onto a smooth nickel under layer a higher nucleation density is obtained so that fewer nodules are produced and the adhesion of the silver is improved. The electrical resistance is close to that expected from the calculated thickness, indicating that a uniform homogeneous coating has been obtained. There is little evidence of cracking in the layers. It appears,

therefore, that the silver layer, in addition to reducing the overall resistance along the coated fibre, improves the physical properties in three respects. Firstly, being a softer material, it fills in and cements together any cracks which are present in the nickel layer and thus helps to maintain electrical contact between the nickel and the fibre. Secondly it provides a source of mobile ions to diffuse into cracks formed in the nickel during operation, which again helps to maintain the electrical performance of the layer. Thirdly it reduces thermal gradients in the coating and thereby minimises stresses due to differential expansion.

The basic requirements for the materials of the two layers are as follows:-

First Layer: high nucleation density on carbon fibre, preferably with some mechanism in the plating process, to limit the growth of large nodules. In other words, the ability to form thin homogeneous layers with smooth surfaces. Such layers may be internally stressed, and may tend to crack.

Second Layer: high nucleation density on first material, giving homogeneous layer. As plated, the material should have little internal stress, and should be of a thickness and resistivity appropriate to the application envisaged. In addition, the material should be capable of rapid surface diffusion, giving the ability to seal major defects occuring in the underlayer during brush operation.

It may be advantageous in some cases to have a coating composed of more than two layers with the electrical and mechanical properties graded from the inside layer to the outside layer.

SUBSTITUTE

REMPLACEMENT

SECTION is not Present

Cette Section est Absente

United States Patent

Wilkin et al.

[15] **3,648,088**

[45] **Mar. 7, 1972**

[54] CURRENT TRANSFER DEVICES FOR ELECTRICAL MACHINES

[72] Inventors: **Geoffrey Alan Wilkin; Ian Roderick McNab; Anthony Derek Appleton,** all of Newcastle, England

[73] Assignee: **International Research & Development Company Limited,** Fossway, Newcastle upon Tyne, England

[22] Filed: **Feb. 5, 1971**

[21] Appl. No.: **112,876**

[30] **Foreign Application Priority Data**

Feb. 5, 1970 Great Britain 5,643/70

[52] **U.S. Cl.** **310/178,** 310/219

[51] **Int. Cl.** **H02k 31/02**

[58] **Field of Search** 310/138, 231, 219, 239, 178, 310/175

[56] **References Cited**

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Primary Examiner—D. F. Duggan
Attorney—Kemon, Palmer & Estabrook

[57] **ABSTRACT**

Current transfer system for homopolar machines and other electrical machines having a direct current circuit passing from the stator to the rotor by way of a first brush and contact ring set and back from the rotor to the stator by way of a second brush and contact ring set, in which the brushes are on the stator in one set and on the rotor in the other set so that current flow between brushes and contact rings is in the same direction for both sets, preferably from the contact ring to the brush, thereby reducing brush wear.

6 Claims, 2 Drawing Figures

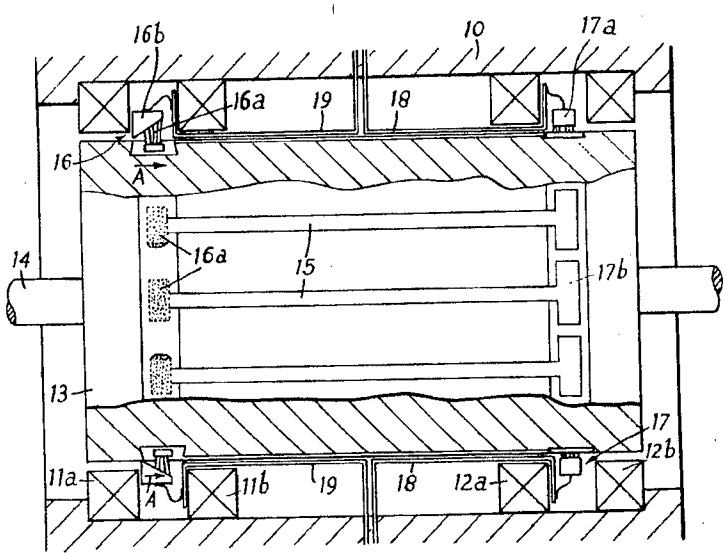


FIG. 1

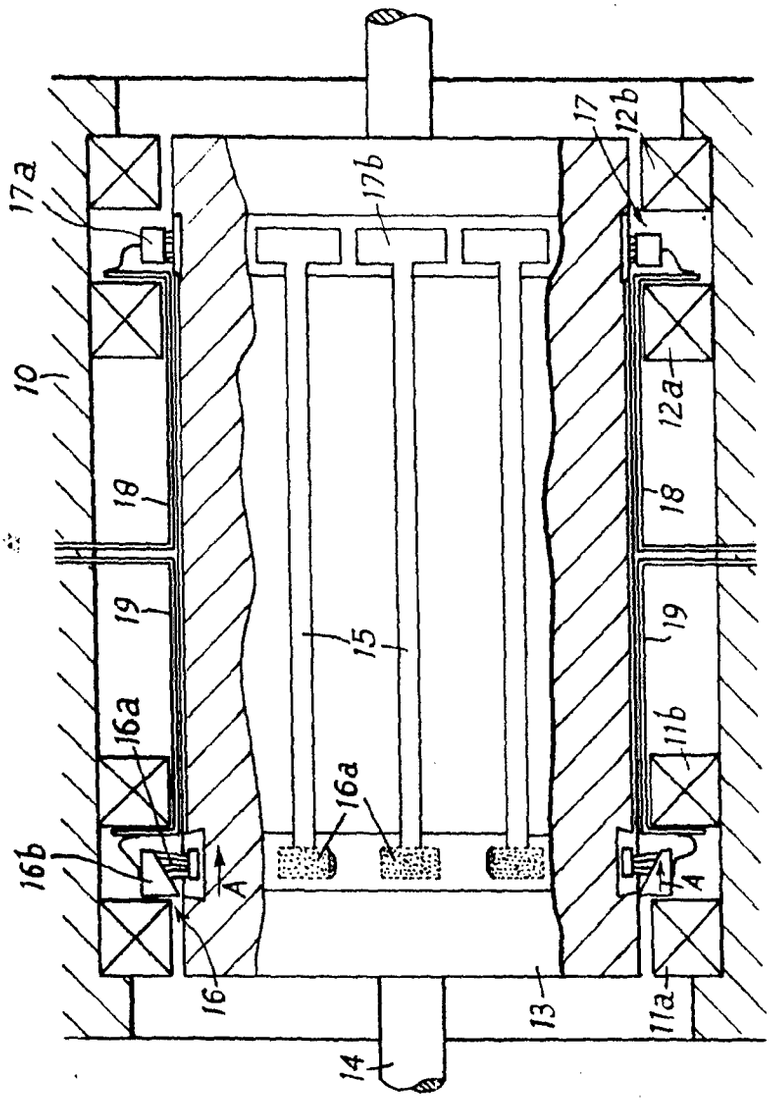
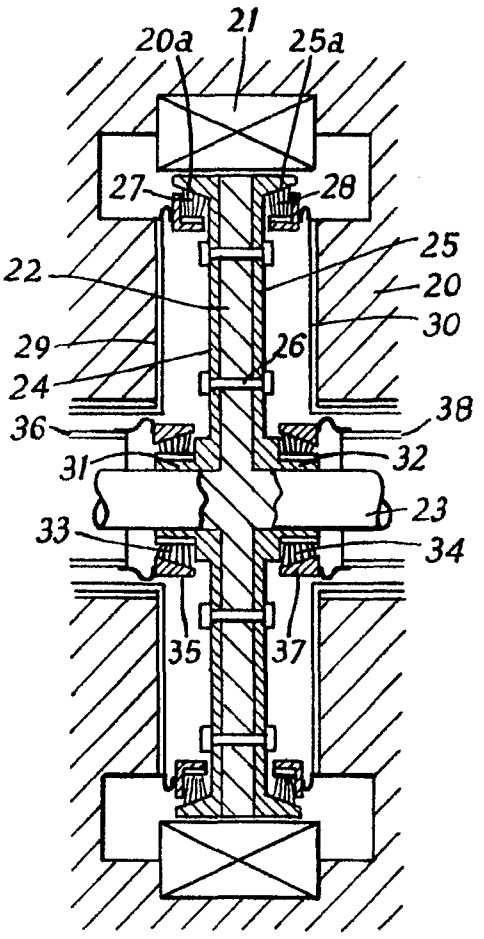


FIG. 2.



CURRENT TRANSFER DEVICES FOR ELECTRICAL MACHINES

This invention relates to current transfer in dynamo-electric machines and is concerned particularly with machines in which current transfer takes place between brushes of electrically conducting material and contact surfaces of electrically conducting material, there being relative rotation between the brushes and the contact surfaces, and the direction of current flow between each brush and the associated contact surface remains constant. Typical of such machines are homopolar machines and synchronous electrical machines where, for example, a direct current is fed through brushes into slip rings on a rotor to provide excitation for a field winding mounted on the rotor.

The problems presented by brush wear and electrical losses on homopolar machines are acute because of the high currents which are transmitted by the current transfer brushes. Brush wear can also be a problem in large turbogenerators where high currents need to be transferred at high rotational speeds.

In accordance with the present invention there is provided a dynamoelectric machine comprising a rotor and a stator, a direct current circuit extending from the stator to the rotor and back to the stator, first current transfer means in the said circuit for conveying current from the stator to the rotor, and second current transfer means in said circuit for conveying current from the rotor to the stator, each of the current transfer means comprising at least one brush and a contact surface movable relative to and cooperating with said brush for the transfer of current therebetween, the brush of the first transfer means and the contact surface of the second transfer means being mounted on the rotor and the brush of the second transfer means and the contact surface of the first transfer means being mounted on the stator, whereby the direction of current flow between the brush and the contact surface is the same for each of the current transfer means.

Preferably the direction of current flow is from the contact surface into the brush, that is electrons pass from the brush to the contact surface.

It is found that this arrangement of the brushes and contact surfaces results in reduced brush wear.

The contact surfaces may be in the form of continuous slip rings or may be composed of individual mutually insulated segments. The brushes may be of carbon and may be arranged individually around a contact surface or form a substantially continuous ring. The brushes may be composed of arrays of carbon fibers either in the form of individual brushes or as a continuous ring.

To allow for wear the contact surfaces may be frustoconical and be urged under a spring force in a direction transverse to the contact face of the brush, the movement being in a direction such that any gap forming between the brush and the surface is taken up.

The invention will now be described in more detail with the aid of examples illustrated in the accompanying drawings, in which:

FIG. 1 is a section of a homopolar electrical machine having a drum type rotor and current transfer means in accordance with the invention, and

FIG. 2 is a section of a homopolar machine with a disc rotor and current transfer means in accordance with the invention.

The homopolar electrical machine shown in FIG. 1 has a stator **10** which carries a first field coil composed of parts **11***a* and **11***b* and a second field coil composed of parts **12***a* and **12***b*. The field coils can be of superconducting material in which case they are enclosed in a cryogenic envelope in a conventional manner to maintain the low operating temperature which is required. In the case of superconducting coils no magnetic core is required on the stator. Alternatively the field coils can be of normal conducting material and in this case are disposed in a magnetic core on the stator **10** in conventional manner. The machine has a drum motor **13** which rotates within the stator on a shaft **14** and which carries on its periphery conducting paths **15** formed by a plurality of individual conductors extending axially of the rotor **13**. Alternatively the rotor may carry a single conducting path consisting of a continuous cylindrical sleeve on the surface of the rotor.

At the ends of the conducting paths **15** on the rotor **13** there are current transfer devices **16** and **17** which serve to transfer current between the stator **10** and the conducting paths on the rotor **13**. The current transfer device **16** comprises a plurality of carbon brushes **16***a* mounted on the rotor for rotation with the rotor. The brushes **16***a*, each of which is composed of an assembly of carbon fibers, can form a complete ring extending substantially continuously around the periphery of the rotor. The current transfer device **16** also comprises a frustoconical contact ring **16***b* which is mounted on the stator **10** between the parts **11***a* and **11***b* of the field coil. The contact ring **16***b* is biassed in the direction of the arrows A by a spring (not shown) so that brush wear is compensated for by axial movement of the contact ring.

The current transfer device **17** comprises a number of brushes **17***a* mounted on the stator **10** and engaging a contact surface composed of a ring of contact segments **17***b* on the rotor. Each of the contact segments **17***b* is connected to one end of a rotor conductor **15**, whose other end is connected to one of the brushes **16***a*. The contact segments **17***b* are mutually insulated from one another. The brushes **17***a* are located between the two parts **12***a* and **12***b* of the field coil on the stator **10**.

The brushes **17***a* on the stator are connected by leads **18** to one terminal of the machine while the contact ring **16***b* is connected by leads **19** to the other terminal of the machine. Current flow thus proceeds from this other terminal through the leads **19** to the contact ring **16***b* and thence into the brushes **16***a*. It then flows through the rotor conductors to the contact segments **17***b* and from them into the brushes **17***a* and by way of leads **18** to the external circuit. In each of the current transfer devices the current flow is from the contact surface into the brush and it is found that the electrical losses and brush wear rate are considerably improved over arrangements in which the direction of current flow is different in each current transfer device.

In an alternative arrangement the direction of current flow is reversed but again the direction of flow is the same in both current transfer devices. The arrangement is applicable to machines acting as motors or generators.

The contact segments **17***b* are shown as presenting a cylindrical contact surface and the brushes **17***a* are biassed against this surface in a radial direction in conventional manner. It is of course possible to use a frustoconical contact surface in the transfer device **17** as in the device **16** and to bias the brushes axially against the contact surface. Whereas the brushes **16***a* and **17***a* are composed of carbon fibers in the embodiment shown, and these fibers can be metal coated, it is also possible to use conventional carbon block brushes.

FIG. 2 shows the application of the invention to a homopolar machine with a disc rotor. The machine has a stator **20** which supports a superconducting field coil **21**. A rotor support disc **22** is carried by a shaft **23** which is mounted in bearings (not shown) in the stator. On either side of the support disc **22** are conducting disc **24** and **25**, for example of copper, which are secured by studs **26**. The outer periphery of each of the discs **24** and **25** has a flange which presents a contact surface **24***a* and **25***a*, respectively, of frustoconical form towards the rotor axis. These contact surfaces **24***a* and **25***a* are engaged by stationary brushes **27** and **28**, respectively, which are mounted on the stator structure **20** and are connected to the external circuit by conductors **29** and **30**, respectively.

The inner regions of the discs **24** and **25** have cylindrical extensions **31** and **32**, respectively, which house brushes **33** and **34**, respectively. The brushes **33** engage a fixed contact ring **35** which is connected to the external circuit by conductors **36**. The brushes **34** engage a fixed contact ring **37** which is connected to the external circuit by conductor **38**.

The two discs **24** and **25** are connected in separate circuits each of which includes two current transfer devices, one for transferring current from the stator to the rotor and one for transferring the current from the rotor to the stator and in each circuit the direction of current flow is the same for each current transfer device. Thus one circuit runs from the contact ring **35** to the brushes **33**, through the disc **24** to the contact surface **24***a* and thence to the brushes **27**. The other circuit is from the contact ring **37** to the brushes **34**, through the disc **25** to the contact surface **25***a* and thence to the brushes **28**.

Each of the brushes **33** and **34** which rotate with the rotor may be a continuous ring of carbon in solid or fiber form or may be composed of several discrete brushes. The contact rings **35** and **37** may be urged in an axial direction by springs (not shown) to compensate for brush wear.

The attitude of the interface between each set of brushes and the associated contact surface is preferably arranged to follow the direction of the magnetic field lines in that region in order to avoid a voltage being developed across the interface.

If the discs **24** and **25** are segmented as described in our U.S. Pat. No. 3,497,739, each rotor disc will be divided up into separate mutually insulated radial conducting paths each connected to a separate insulated segment on the outer flange and on the inner cylindrical extension. The brushes will be discrete brushes spaced by at least one segment width around the outer flange and inner cylindrical extension. The electrical connections will be such as to connect selected conducting paths in series as the rotor rotates. The contact rings **35** and **37** will also be segmented with insulation between the conducting segments.

The brushes may be held in position by conventional brush holders or if fiber brushes are used the arrays or bundles of fibers can be held in crimped tubes.

Whilst the invention has been described with particular reference to homopolar machines it can also be applied to synchronous machines where direct current is transferred through slip-rings to a rotor winding.

Whilst carbon brushes have been described other brush materials can be used such as metal brushes, composite metal-graphite brushes or metal such as silver with molybdenum disulphide.

We claim:

1. A dynamoelectric machine comprising a rotor and a stator, a direct current circuit extending from the stator to the rotor and back to the stator, first current transfer means in the said circuit for conveying current from the stator to the rotor, and second current transfer means in said circuit for conveying current from the rotor to the stator, each of the current transfer means comprising at least one brush and a contact surface movable relative to and cooperating with said brush for the transfer of current therebetween, the brush of the first transfer means and the contact surface of the second transfer means being mounted on the rotor and the brush of the second transfer means and the contact surface of the first transfer means being mounted on the stator, whereby the direction of current flow between the brush and the contact surface is the same for each of the current transfer means.

2. A dynamoelectric machine as claimed in claim **1** wherein the direction of current flow in the direct current circuit is from the contact surface into the brush.

3. A dynamoelectric machine as claimed in claim **1** in which each of the contact surfaces comprises a plurality of mutually insulated electrically conductive segments.

4. A dynamoelectric machine as claimed in claim **1** in which each brush comprises a block of carbon.

5. A dynamoelectric machine as claimed in claim **1** in which each brush comprises an array of carbon fibers.

6. A dynamoelectric machine as claimed in claim **1** in which the contact surfaces are frustoconical and are biassed against the brushes by force applying means acting in a direction transverse to the brushes.

* * * * *

United States Patent [19]

Wilkin et al.

[11] **3,821,024**

[45] **June 28, 1974**

[54] **CURRENT TRANSFER BRUSHER**

[75] Inventors: **Geoffrey Alan Wilkin; Ian Roderick McNab,** both of Newcastle-upon-Tyne, England

[73] Assignee: **International Research & Development Company Limited,** Fossway, England

[22] Filed: **Feb. 23, 1973**

[21] Appl. No.: **335,331**

[30] **Foreign Application Priority Data**

Feb. 29, 1972 Great Britain 9256/72

[52] **U.S. Cl.** **117/217,** 117/228, 310/252

[51] **Int. Cl.** **C23b 5/50**

[58] **Field of Search** 310/219, 231, 245, 248–253; 117/217, 228, 71

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Primary Examiner—R. Skudy

Attorney, Agent, or Firm—Kemon, Palmer & Estabrook

[57] **ABSTRACT**

A current transfer brush is composed of refractory fibres, preferably high strength carbon fibres, with a metallic coating on the fibres which is composed of an under layer of a first metal and an over layer of a second metal. The over layer is of a highly conductive material such as silver and the under layer which improves coherence and adhesion of the over layer and thereby produces a very low brush voltage drop, is of a material such as nickel.

7 Claims, 2 Drawing Figures

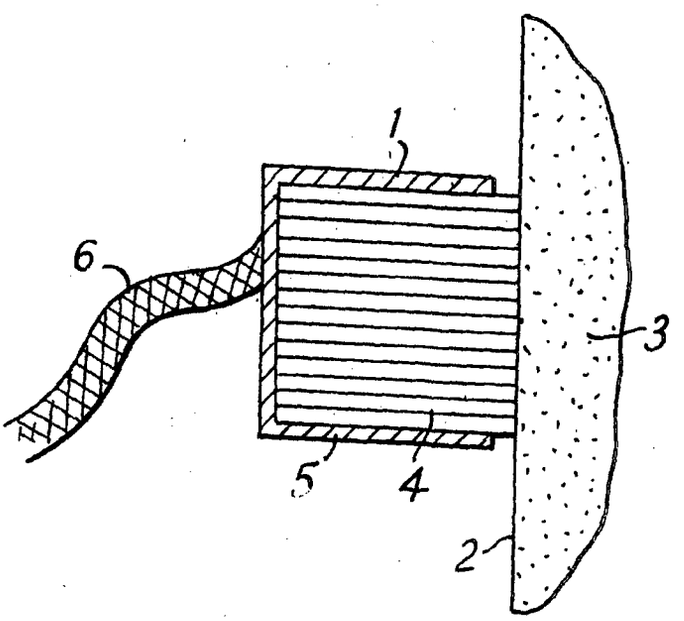


FIG. 1

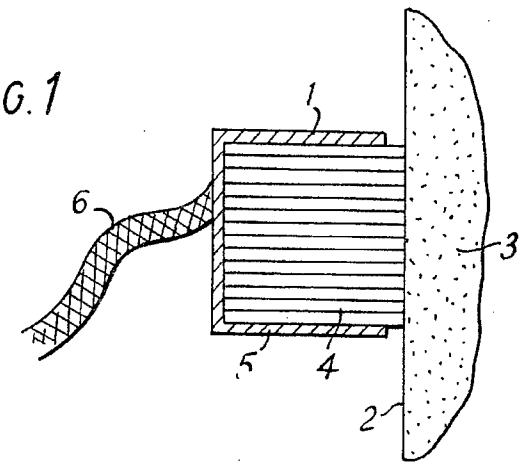
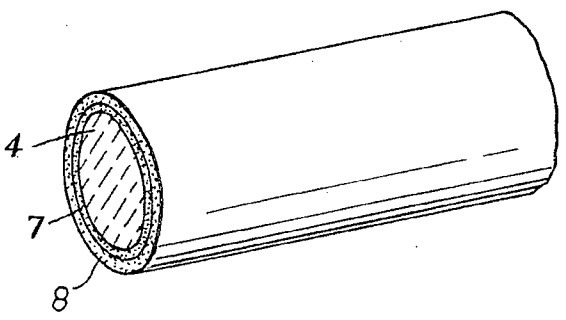


FIG. 2



CURRENT TRANSFER BRUSHER

The present invention relates to current transfer brushes consisting of refractory fibres, such as carbon fibres, coated with an eletrically-conductive metallic layer.

Such brushes form the subject of our British Pat. No. 1,191,234, French Pat. No. 70,30073 and U.S. Pat. No. 3,668,451 and are particularly valuable for use in homopolar machines where high speeds of rotation and large currents call for brushes which exhibit a low rate of wear when rubbing against a rapidly moving contact surface and which have high electrical conductivity. In these prior brushes the carbon fibres which are employed have very good mechanical properties because of their special method of production and they provide support for the layer of electrically conductive metal, such as silver, which probably carries most of the current. The thickness of the layer is limited because it is essential to maintain the flexibility of the fibre in order to give satisfactory wear rates. Therefore the electrical conductivity cannot be increased simply by using a thicker coating. Unfortunately it is found in practice that a layer of a particular thickness, calculated from the weight deposited per unit area, gives a conductivity lower by a factor of 10 or more than the expected value. Moreover the conductivity, and thus the voltage drop at the brush, varies from one sample to another and is different according to whether the brush is connected as a negative brush (from which electrons flow into the contact surface) or a positive brush (into which electrons flow from the contact surface).

The problem underlying the invention, therefore, is to improve the electrical properties of metal-coated fibre brushes without harming their mechanical properties and thereby suffering from increased wear rates. In accordance with the invention the solution to this problem is found in the provision of a brush composed of refractory fibres each of which has a metal coating composed of two layers of which the under layer is a homogeneous layer with a smooth surface while the outer layer is of high electrical conductivity, forms a homogeneous coating on the under layer, and has a high ionic mobility giving it the capacity for rapid diffusion across the surface of the under layer to fill cracks which may occur during operation.

It is believed that the formation of a satisfactory underlayer with good adhesion to a carbon fibre may require the formation of a thin carbide phase between the fibre and the underlayer. Hence the metals to be used for the underlayer are those with reasonably stable carbides namely titanium, vanadium,tantalum, chromium, molybdenum, tungsten, manganese, iron, cobalt, nickel, and boron. Of these the preferred materials are chromium, iron, cobalt, and nickel.

For the outer layer silver is the preferred material because of its high electrical conductivity and its resistance to oxidation. Gold also has suitable properties but is unlikely to be used because of its high cost. If the brushes are to be run in a reducing atmosphere, thereby avoiding the risk of oxidation, it is possible to use copper, aluminium, cadmium, zinc or lead, copper being preferred. It is also possible to use an alloy of silver and copper.

With a two-layer coating it has proved possible, for a coating of the same overall thickness, to obtain higher conductivity, i.e., lower voltage drop, than is possible

with a single layer of either of the coating materials. This voltage drop is less variable from sample to sample and is less dependent on the direction of current flow between the brush and the contact surface. Moreover these results are obtained without any deterioration in the wear rate, in fact at high current densities there is even some reduction in the rate of wear, perhaps resulting from improved adhesion of the outer layer to the under layer under conditions of high thermal stress as compared with the adhesion of the material of the outer layer to the surface of the fibre.

A variety of deposition processes can be used for applying the two layers to the refractory fibres. The preferred process is that of electro-plating and details of how this may be applied are given in our British Pat. specifications Nos. 1,272,777 and 1,309,252. Other processes available include pyrolysis of an organometallic vapour, high vacuum evaporation, sputtering, and electroless plating (that is chemical reduction of metallic salts).

By way of example one embodiment of this invention will now be described in more detail and comparative information will be given to show how this embodiment with a two-layer coating affords substantially better results than a single layer of either of the coating materials separately. In this embodiment carbon fibres are coated with an under layer of nickel and an outer layer of silver.

The carbon fibres used are high strength fibres of RAE Type II produced as described in British Pat. specification No. 1,110,971 by carbonization of polyacrylonitrile fibres while holding them under tension. The average diameter of the filaments is 7.5 μ m. When such filaments are electroplated with silver to give an average coating thickness, calculated in terms of the amount of metal deposited per unit length of a tow consisting of as many as 10^4 fibres, of 1.0 μ m the electrical resistance is found to be 10 to 20 times higher than would be expected with a uniform layer of this thickness. This is thought to be due to the fact that the silver deposit is nodular and has areas of poor adhesion to the carbon fibre.

If such carbon fibres are electroplated with nickel alone as a single layer a smoother, more homogeneous deposit is formed and the electrical properties are more consistent. There is better correlation between the calculated layer thickness and the actual conductivity but the overall voltage drop is generally higher than for a silver layer.

If now a silver layer is electroplated onto a nickel layer there is a marked improvement in the electrical and mechanical properties. Measurements of voltage drop made with brushes running at a speed of 35m/sec on a silver-plated slip ring with a current density of 500 KA/m^2 are given in the following table for the various types of brush

Fiber coating	Positive Brush	Negative Brush
Nickel	1.5	0.40
Silver	1.2	0.25
Silver on nickel	0.20	0.15

The average coating thickness, as calculated from the weight of material applied, was approximately 1μ m for the silver layer alone, 0.7μm for the nickel layer alone, and 0.5μ m of silver over 0.7μ m of nickel.

In the case of a nickel-coated positive brush the initial voltage drop was similar to that of a negative brush but within a few seconds of commencing operation it rose to the higher value given in the table.

It will be seen from the table that in addition to the low value of voltage drop obtained for a negative brush with a two-layer coating there is a very important improvement in the voltage drop for a positive brush so that the performance of the brush is largely independent of the direction of current flow.

A silver layer applied directly to the carbon fibre by electro-plating from an alkali cyanide bath is nodular and shows areas of poor adhesion where the material will readily flake off under mechanical stress. It is believed that the unevenness of the deposit and its lack of adhesion are responsible for the fact that the resistance per unit length is 10 to 20 times higher than would be expected from the calculated average layer thickness. A nickel layer plated from an acid bath gives a more smooth and homogeneous layer which despite the presence of longitudinal cracks showed little tendency to flake off. The correlation between resistance and calculated layer thickness was better than with silver.

When silver is plated onto a smooth nickel under layer a higher nucleation density is obtained so that fewer nodules are produced and the adhesion of the silver is improved. The electrical resistance is close to that expected from the calculated thickness, indicating that a uniform homogeneous coating has been obtained. There is little evidence of cracking in the layers. It appears, therefore, that the silver layer, in addition to reducing the overall resistance along the coated fibre, improves the physical properties in three respects. Firstly, being a softer material, it fills in and cements together any cracks which are present in the nickel layer and thus helps to maintain electrical contact between the nickel and the fibre. Secondly it provides a source of mobile ions to diffuse into cracks formed in the nickel during operation, which again helps to maintain the electrical performance of the layer. Thirdly it reduces thermal gradients in the coating and thereby minimises stresses due to differential expansion.

The basic requirements for the materials of the two layers are as follows:

First Layer: high nucleation density on carbon fibre, preferably with some mechanism in the plating process, to limit the growth of large nodules. In other words, the ability to form thin homogeneous layers with smooth surfaces. Such layers may be internally stressed, and may tend to crack.

Second Layer: high nucleation density on first material, giving homogeneous layer. As plated, the material should have little internal stress, and should be of a thickness and resistivity appropriate to the application envisaged. In addition, the material should be capable of rapid surface diffusion, giving the ability to seal major defects occuring in the underlayer during brush operation.

It may be advantageous in some cases to have a coating composed of more than two layers with the electrical and mechanical properties graded from the inside layer to the outside layer.

One example of the invention is shown in the accompanying drawing, in which:

FIG. 1 is a cross-section of an electrical current transfer brush in accordance with the invention shown in engagement with a current transfer surface, and

FIG. 2 shows on an enlarged scale a fibre with a metallic coating employed in the brush of FIG. 1.

Referring to FIG. 1, an electrical machine comprises a current transfer brush 1 which is in contact with a surface 2 of an electrically conducting member 3. The member 3 may be, for example, a slip ring or commutator segment in a dynamo-electric machine or may be a continuous rail from which the brush 1 collects current, for example for traction purposes in vehicle systems. The brush 1 comprises a plurality of fibres 4 retained in mutual contact with each other along a major part of their length by a casing 5 of metallic material. A braid 6 of electrically conductive material carries current between the brush and windings or terminals of the machine.

Each of the fibres 4, as shown in FIG. 2, has a coating composed of a first layer 7 and a second layer 8. The composition and manner of formation of the fibres 4 and the layers 7 and 8 are as described previously and in this preferred construction high strength carbon fibres 4 are coated first with a nickel layer 7 and then with a silver layer 8. The fibres are held in close contact by the clamping action of the casing 5 and may be welded to each other along a portion of their length by way of the metallic fibres. It is important that the fibres should not be welded together at their free ends adjacent the transfer surface 2 since here they must be free to flex individually.

The braid 6 may be soldered, welded or rivetted to the casing 5 or alternatively may be connected directly to the fibres. The brush may be held in a conventional brush holder which is spring biassed towards the surface 2.

What is claimed is:

1. A current transfer brush comprising refractory fibres individually coated with a coating comprising a homogeneous under layer of a first metal closely adherent to the fibre and an over layer of a second metal with high electrical conductivity which adheres to the under layer.

2. A current transfer brush as claimed in claim 1 in which the under layer is composed of a metal selected from the group comprising titanium, vanadium, tantalum, chromium, molybdenum, tungsten, manganese, iron, cobalt, nickel, and boron.

3. A current transfer brush as claimed in claim 2 in which the over layer is of silver.

4. A current transfer brush as claimed in claim 1 in which the over layer is selected from the group comprising silver, gold, copper, aluminium, cadmium, zinc, and lead.

5. A current transfer brush comprising refractory fibres each of which is coated with an under layer of a metal selected from chromium, iron, cobalt, and nickel and an over layer of a metal selected from silver, gold, copper, and alloys of silver and copper.

6. A current transfer brush as claimed in claim 5 in which the fibres are carbon fibres.

7. A current transfer brush as claimed in claim 6 in which the under layer is of nickel and the over layer is of silver.

* * * * *

APPENDIX G: Current Collection Workshop Presentation

Homopolar Machines and Brushes

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Email: mcnab@iat.utexas.edu
19 February 2004

Part 1 – Superconducting Homopolar Machine Developments

SC HPG Developments

- IRD Co. (Newcastle, UK) from 1964-75
- Westinghouse R&D (Pittsburgh) from 1970-80
- USN (Annapolis) from 1970-1983
- GA/ONR

The First Motor (IRD Co.)

IRD model SC Motor

- Tested in June 1966
- First SC HPM
- 50 hp at 2000 rpm
- Double-disk geometry rotor
- 7-strand NbTi winding
- Peak field at winding = 2.7 T
- V_{gen} = 9.35 V
- I = 3.5 kA
- Morganite Cu-gr brushes
- Unacceptable losses and brush debris

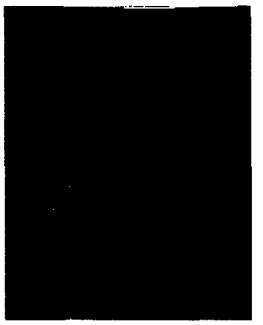
The Fawley Motor (IRD Co.)

IRD 3250 hp motor

- Design started 1967
- Tested in October 1969
- 200 rpm
- 3947 turns of NbTi of 10 x 1.8 mm
- 725 A gave 3.7 T
- 6.6 Wb flux
- Warm bore 2.2 m
- Outer diameter 2.8 m
- Double segmented disks
- Stage voltage = 42 V
- Terminal voltage = 440 V
- 50 W BOC refrigerator (at 4.4K)

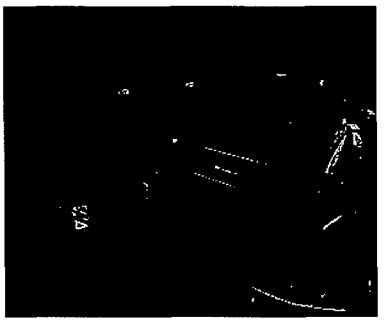
Fawley motor rotor

- Partially assembled armature of Fawley motor
- Multiple rotor segments were connected in series
- High brush wear occurred when brushes left the trailing edge of a segment
- The solution was to have a "dead" segment between active ones
- The stator segments were connected in two parallel circuits



Motor installed at Fawley

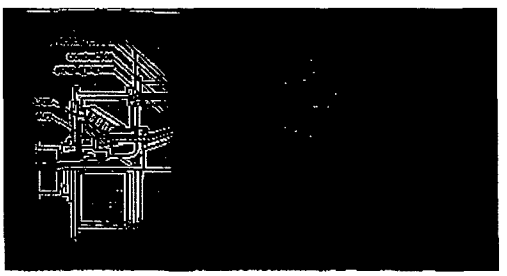
- Installed in 1970
- Drive for a 500 MW turboalternator cooling water pump
- Tests began in Jan 1971
- Full power by March 1971
- Helium compressor unreliability
- No brush sparking at the segmented sliprings



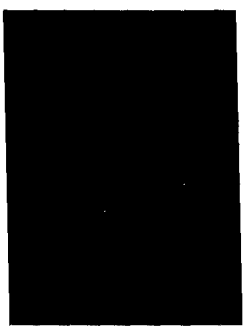
MOD(N) minesweeper motor-generator (IRD Co.)

Minesweeper motor layout

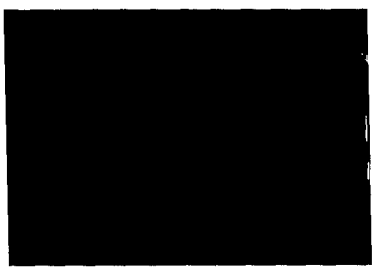
Minesweeper generator



Coil assembly into stator



Minesweeper generator rotor



Assembly area - 1

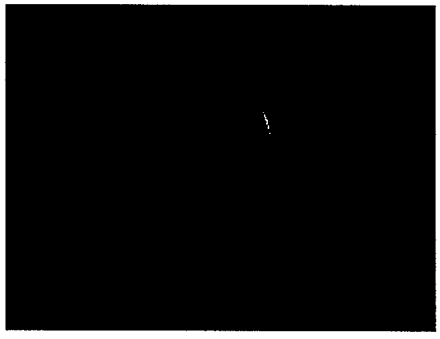
Assembly area - 2

Rutherford generator (IRD Co.)

Generator cross-section

Rutherford rotor

Generator & drive motor



Rutherford generator CF brushes

Constant force ("tensator") springs were used

Lessons learned

Observations:

- Homopolar machines are basically simple and robust
- They are intrinsically low voltage (V_s), high current (I_s) machines
- Multi-staging can improve the terminal characteristics: nV_s and I_s/n
- There is no armature reaction on the field windings
- All the machine power goes through the brush/slipring interface

Lesson:

- The "brush" designer has to be an integral part of the machine design process – brushes cannot just be inserted after the machine is built

Brush Features

What we want (and why):

- Low electrical contact drop (losses)
- Low friction coefficient (losses)
- Long brush life (minimal maintenance & cost)
- Long slipring life (no machine refurbishment)
- Minimal necessary auxiliaries (cost & complexity)

What we *don't* want (and why):

- Brush (& slipring) wear debris (machine failure & maintenance)

A few other things.....

- Current sharing
- Brush contact stability
- Slipring wear and deterioration
- Slipring grooves
- Rotor reversal for a motor
- Atmosphere control
- Debris removal
- Operating conditions (speed, current density, etc)

Brush selection

- Machine designers should assess all options and choose the most appropriate for their application
- Brush choices:
  - Conventional metal-graphite grades
  - Fiber brushes
    - Carbon fibers
    - Metal-plated carbon fibers
    - Metal fibers
  - Metal foil
  - Liquid metals

Liquid metals - 1

- Mercury
  - First used by Faraday in 1830's
  - High density causes high viscous losses
  - Toxicity makes it unacceptable
- NaK (and Na)
  - Used by Allis Chalmers in 1960's HPGs, ANU HPG in 1970's, by Westinghouse and by USN Annapolis
  - Reactive with water and forms explosive superoxides
  - Accidents have happened
  - Continuous purification loops needed
  - Annapolis porous brush approach seemed best
  - Not a good choice for a ship main propulsion system

Liquid metals - 2

- Low melting point elements and alloys
  - Indium, tin, gallium, lead
  - Intermediate density gives moderate viscous losses
  - Strong tendency to oxidize demands atmospheric control
  - Oxidation cause high viscosity and even solidification
  - Annapolis are the experts in recent times
- My conclusion –liquid metal solutions are not yet attractive

Conventional brushes

- Initial high current tests done with copper-graphite brushes (Morganite grade CM1S)
- Choice was based on experience at ANU homopolar generator in Canberra
- Brush life was an issue
- Utility turboalternators used pure graphite brushes for high speed long life operation – but contact voltage drops were too high for HPs
- Alternatives sought

Carbon fiber brush development (IRD Co.)

Early days

- First suggestion of possibility of using carbon fibers as a brush made by Sam Bolshaw (Scientific Advisor to MOD-N) in ~ 1967
- Idea was that flexible carbon fibers (just then being produced) would provide a stable and large contact area with the slipring
- Initial brushes made and tested by IRD
- Performance improved with time
- Evaluation showed that slipring wear debris was being embedded in the brush and provided increased contact
- IRD decided to try to make metallic plated fibers

Carbon fiber plating bath

- A wet electroplating process was developed
- Delivered tows contained 10,000 fibers
- Fibers were unrolled off shipping drums and passed through a multistage bath process
- Steps included:
  - spreading the fibers
  - removing surface treatments
  - sensitizing the surface
  - laying down an initial coating
  - plating
  - drying
  - winding onto drums

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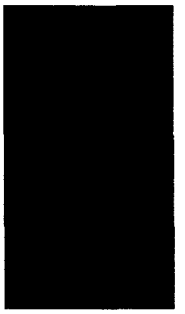
Plated carbon fibers

- The products created were evaluated for macroscopic and microscopic quality
- Samples included silver-plated carbon fibers
- Typical fiber diameter ~ 7 microns
- Typical plating thickness ~ 1 micron



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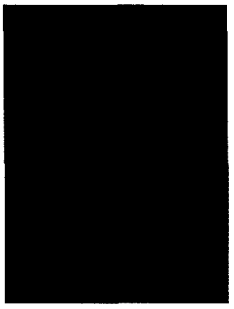
Single fiber brush

- In the manufacturing process, multilayers of fibers were laid up in a jig
- Required lengths were cut up
- Early fiber brushes were crimped
- Later (lower cost) brush backs were plasma sprayed and soldered
- This assembly was then soldered to a backing plate that had electrical connections attached



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Brush testing

- Tests were undertaken over a wide range of conditions:
  - speed
  - current density
  - brush plating
  - slipring material
  - atmosphere
  - paralleled brushes
- Generator operation more stressing (much higher speed) than motor opn.

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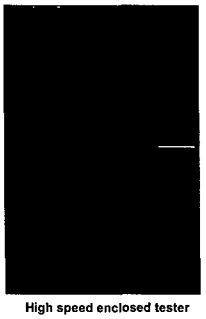
Multiple test rigs used



High speed enclosed tester

Small controlled environment tester

Rotating brush tester

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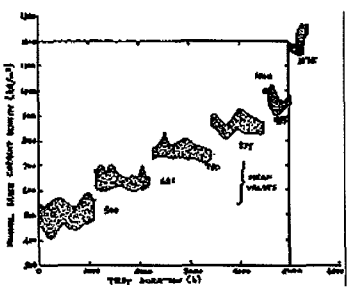
Test data example

- Long duration (5500 hr.) multiple brush test
- Silver-plated carbon fibers on a silver slipring (probably)
- Reducing humidified atmosphere
- Current density increased (deliberately) during test
- Data shows nominal fiber brush current density
- Slipring speed ? (probably moderately high)



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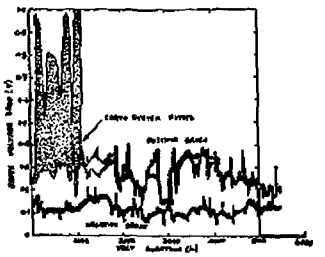
Test data example

- Measured fiber brush voltage drops
- Positive brush has higher drop
- Positive brush is much less stable than the negative brush
- A servo-controlled brush wear adjustment system was installed and helped to stabilize the positive voltage – but differences still remained



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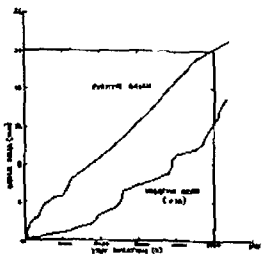
Fiber brush test data

- Fiber brush wear rates were measured in the 5000 hr. test
- The negative brush wear was remarkably low: 10 mm in 5000 hrs.
- The positive brush wear was much (x 20) higher
- Multiple approaches were pursued to evaluate reasons and seek solutions



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- Define M parameter to assess the effect of the induced voltage on the brush and slipring
- $M = V_T / 2 V_B$

(where $V_T = B_{radial} VL$ and V_B = brush voltage drop)

- Recommend M ~ 0.1 for minimal effect

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Rotating brush rotor

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Face-mounted rotating brush

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Magnetic field test rig

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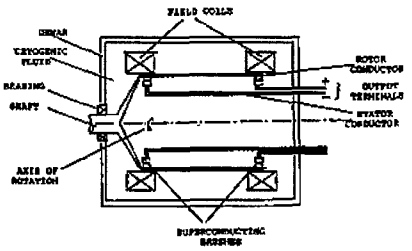
The Ultimate HPG Brush ?

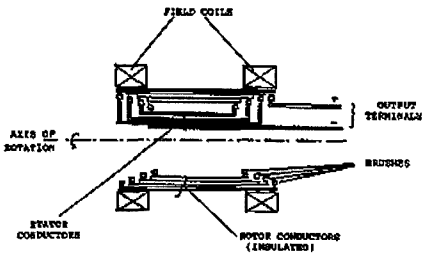
- Concept:
  - Make brushes of superconducting wire
  - Run them in the cryogenic fluid (LN_2 or LHe)
- Idea first described in Westinghouse Patent Disclosure RES 75-274. 13 June 1975
- Proof of possibility: B.L. Blackford, et. al. showed that a wire could remain superconducting while in sliding contact with a slipring (*Cryogenics*, Vol 4. May 1975. p. 94.
- Discussed at the International Current Collector Conference, UT Austin. 16-17 Nov 1987
- Big issue – will the frictional heat of sliding make the contact go normal.
- Big advantage – the whole machine is superconducting, so all electrical losses are reduced and efficiency goes up
- Recommendation – ONR fund some experiments to try it !

All-superconducting machine



From: "Superconducting Brushes and Machines" by I.R. McNab presented at the International Current Collector Conference, University of Texas. 16-17 November 1987.

Multi-stage All-SC machine



From: "Superconducting Brushes and Machines" by I.R. McNab presented at the International Current Collector Conference, University of Texas. 16-17 November 1987.

Summary

- Significant advances have occurred in EM Launch technology
  - gouging is understood and overcome
  - advances in understanding transition are being made
  - barrel lifetime remains an issue
  - state-of-the-art fast computing tools are being improved
- Pulsed Power developments are taking place
  - pulsed alternator modeling is advancing
  - switch technology improvements being quantified
  - hybrid electric vehicle modeling
  - power system size remains an issue
- System integration issues are starting to be addressed
- Better definition of mission requirements is needed to drive the technology
- Non-direct fire applications are also being evaluated

A vigorous and productive IAT team is supporting the National U.S. EM gun program